IAEA Review of Safety-Related Aspects of Handling ALPS-Treated Water at TEPCO's Fukushima Daiichi Nuclear Power Station

Corroboration of External Exposure Monitoring

Performance of Whole-Body, Extremity and Eye-Lens Dosemeters

IAEA
International Atomic Energy Agency

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EXECUTIVE SUMMARY

In 2021, the International Atomic Energy Agency (IAEA) started its review of safety-related aspects of handling Advanced Liquid Processing System (ALPS)-treated water at Tokyo Electric Power Company Holdings' (TEPCO's) Fukushima Daiichi Nuclear Power Station (FDNPS). Consistent with the request from the Government of Japan, the IAEA statutory functions and the mandate of the Task Force, the scope of the IAEA review is tailored to assessing safety related aspects of the implementation of Japan's *Basic Policy on Handling of ALPS-Treated Water at the Tokyo Electric Power Company Holdings' Fukushima Daiichi Nuclear Power Station* against the IAEA Safety Standards. The current approach outlined in the Basic Policy is to conduct a series of controlled discharges of ALPS-treated water into the sea ('batch discharges') over a period of decades.

Consistent with the relevant IAEA Safety Standards, TEPCO bears the responsibility for the protection of workers against occupational exposure to ionizing radiation. An individual monitoring programme was arranged with approved dosimetry services that operate under a quality management system to assess radiation doses to workers arising from exposure to external sources of radiation and from exposure due to intakes of radionuclides. The IAEA's data corroboration focuses on assessment of the capabilities of dosimetry service providers contracted by TEPCO who are monitoring external and internal radiation exposure of workers involved in handling ALPS-treated water at FDNPS.

To conduct its safety review, the IAEA has organized the work of the Task Force into three main components: the assessment of protection and safety; regulatory activities and processes; and sampling, independent analysis and data corroboration. The latter activities include three elements:

- sampling, analysis and interlaboratory comparison for ALPS-treated water from the FDNPS;
- sampling, analysis and interlaboratory comparison for environmental samples (e.g., seawater, fish) from the surrounding environment of FDNPS; as well as
- assessment of the capabilities of dosimetry service providers involved in the monitoring of internal and external radiation exposure of workers at FDNPS.

The latter activities also include a review of analytical methods used by TEPCO and its contractors. The corroboration of external and internal radiation exposure monitoring is based on an extensive proficiency testing scheme, which involves interlaboratory comparisons for the determination of laboratory performance, assessment of the quality of measurement results and identification of potential improvements. Proficiency testing involves the evaluation of performance against preestablished criteria whereas interlaboratory comparisons comprise the organization, performance, and evaluation of measurements on the same or similar items by two or more laboratories in accordance with predetermined conditions.

This report presents the results and findings from a proficiency testing scheme organized by the IAEA in 2023/24 to corroborate the capabilities of individual monitoring services contracted by TEPCO for the assessment of external radiation exposure of workers involved in handling ALPS-treated water. A second report focusing on internal radiation exposure monitoring will be published separately. The scheme aimed to improve harmonization of individual monitoring and to demonstrate compliance with international standards and requirements, in particular Radiological Protection — Criteria and Performance Limits for the Periodic Evaluation of Dosimetry Services (ISO 14146:2018).

Phase I was for whole-body dosemeters, and Phase II was for extremity and eye-lens dosemeters. A total of 66 whole-body, 42 extremity and 28 eye-lens dosemeters were irradiated, accommodating integrating passive detectors for photon and beta-particle radiation that are routinely employed to determine personal dose equivalent, $H_p(10)$, $H_p(0.07)$ and/or $H_p(3)$.

Reference irradiations were carried out in accordance with the ISO 4037:2019 and ISO 6980:2023 series of standards by metrology laboratories for ionizing radiation, which are considered as internationally recognized Calibration and Measurement Capabilities (CMCs) by the International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM): the Research Centre for Energy, Environment and Technology (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, CIEMAT), Spain; the IAEA, Austria; the Physikalisch-Technische Bundesanstalt (PTB), Germany; and Seibersdorf Laboratories (SL), Austria.

Radiation qualities, doses and angles of incidence were selected to emulate the workplace exposure conditions and allow for an investigation of accuracy, linearity of response and reproducibility in the following ranges:

<u>Whole-body dosimetry</u>

- Radiation quality: Gamma and X-radiation with mean energies from 33 keV to 662 keV
- Personal dose equivalent, $H_p(10)$ and $H_p(0.07)$: 0.3 mSv to 10 mSv
- Angle of incidence: ± 60°

<u>Extremity and eye-lens dosimetry</u>

- Radiation quality: Beta-particle radiation with maximum energy of 2.274 MeV
- Personal dose equivalent, $H_p(0.07)$ and $H_p(3)$: 1.0 mSv to 10 mSv
- Angle of incidence: ± 45°

The results in terms of energy and angular response with respect to the conventional quantity value as well as reproducibility were all close to unity, with only one outlier (out of 136 dosemeters). As the ISO 14146:2018 approval criterion allows for one-tenth of the dosemeters from a particular dosimetry service irradiated as part of an interlaboratory comparison to exceed the performance limits, it was concluded that proficiency testing for whole-body, extremity and eye-lens dosemeters had been successfully carried out and that all dosimetry services met the approval criterion of ISO 14146:2018 for the irradiations under test, providing for an independent demonstration of the reliability and robustness of the individual monitoring services involved.

The key findings of the reported interlaboratory comparisons are:

- Japanese laboratories have demonstrated a high level of accuracy in their measurements and technical competence.
- Analytical procedures follow the appropriate methodological standards required to obtain technically valid results.

The IAEA notes that these findings provide confidence in Japan's capability for accurate assessment of external radiation exposure of workers involved in handling ALPS-treated water.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

In 2021, the International Atomic Energy Agency (IAEA) started its review of safety-related aspects of handling Advanced Liquid Processing System (ALPS)-treated water at Tokyo Electric Power Company Holdings' (TEPCO's) Fukushima Daiichi Nuclear Power Station (FDNPS). Consistent with the request from the Government of Japan, the IAEA statutory functions and the mandate of the Task Force, the scope of the IAEA review is tailored to assessing safety related aspects of the implementation of Japan's *Basic Policy on Handling of ALPS-Treated Water at the Tokyo Electric Power Company's Holdings' Fukushima Daiichi Nuclear Power Station* against the IAEA Safety Standards. The current approach outlined in the Basic Policy is to conduct a series of controlled discharges of ALPS-treated water into the sea ('batch discharges') over a period of decades.

According to the requirements of *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards* [1], the responsibility for the protection of workers against occupational exposure resides with employers, registrants and licensees who shall ensure that protection and safety is optimized and that the dose limits for occupational exposure to ionizing radiation are not exceeded. Furthermore, appropriate arrangements shall be made with authorized or approved dosimetry services that operate under a quality management system for assessment and recording of the occupational exposure of workers. For workers who usually work in controlled areas, or who occasionally work in controlled areas and may receive a significant dose from occupational exposure, individual monitoring shall be undertaken where appropriate, adequate, and feasible. For workers who regularly work in supervised areas or who enter controlled areas only occasionally, the occupational exposure shall be assessed based on the results of workplace monitoring or individual monitoring, as appropriate. Employers shall ensure that workers who could be subject to exposure due to contamination are identified, and arrangements are made to assess intakes of radionuclides and committed effective doses.

The IAEA's data corroboration focuses on assessment of the capabilities of dosimetry service providers who are monitoring external and internal radiation exposure of workers involved in handling ALPS-treated water at FDNPS, and contains three distinct elements which have been implemented in a phased approach [2]:

- corroboration of external exposure monitoring;
- corroboration of internal exposure monitoring; and
- review of analytical methods in external and internal dosimetry applied by the relevant dosimetry services.

This report presents the results and findings from an extensive interlaboratory comparison (ILC) programme organized by the IAEA in 2023/24 to corroborate the capabilities of individual monitoring services contracted by TEPCO for the assessment of external radiation exposure of workers involved in handling ALPS-treated water. A second report focusing on internal radiation exposure monitoring will be published separately.

In April 2023, the IAEA has initiated an extensive proficiency testing scheme to corroborate the capabilities of individual monitoring services (IMSs) contracted by TEPCO for the assessment of external radiation exposure of workers involved in handling ALPS-treated water. This scheme involved ILCs for the determination of laboratory performance, assessment of the quality of measurement results from whole-body, extremity and eye-lens dosemeters, and identification of potential improvements. Proficiency testing comprises the evaluation of performance against pre-established criteria, whereas ILCs involve the organization, performance, and evaluation of measurements on the same or similar items by two or more laboratories in accordance with pre-determined conditions [3].

The IAEA also conducted a review of analytical methods relevant to external dosimetry used by the dosimetry service providers contracted by TEPCO, who are accredited by the Japan Accreditation Board for Conformity Assessment (JAB). The results of this review contribute to ensuring the validity of the data generated as part of proficiency testing, provide for an independent demonstration of the reliability and robustness of the IMSs involved, and serve the following purposes:

- evaluation of the performance of laboratories for specific measurements;
- identification of inconsistencies in results between laboratories;
- establishment of the effectiveness and comparability of analytical methods;
- provision of additional confidence to interested parties; and
- validation of uncertainties.

1.2. OBJECTIVE

The objective of the ILCs was to demonstrate compliance with ISO 14146:2018 [4] for the approved dosimetry services contracted by TEPCO for the assessment of external radiation exposure of workers involved in handling ALPS-treated water at FDNPS. The ISO standard states:

- "The performance evaluation can be carried out as part of the approval procedure for a dosimetry service or as an independent check to verify that a dosimetry service fulfils specified national or international type test performance requirements under representative exposure conditions that are expected to mimic workplace fields from the radiological activities being monitored".
- "The dosimetry service shall not be aware of the irradiation qualities and doses used for the irradiations". (One of the key roles of the co-ordinator was to separate communications between IMSs and the irradiation laboratories.)
- "The majority of irradiated doses should be similar to the conditions found in routine radiation surveillance in order to prevent evaluations from emphasizing performance under extreme conditions."

ISO 14146 specifies response limits for each irradiated dosemeter in terms of the ratio of the dose reported by the IMS and the reference dose as reported by the irradiating laboratory. This is explained in detail in Chapter 2.

A particular objective of this ILC was to present all the results promptly and clearly (with graphical and numerical information) to all participating IMSs in terms of compliance with the ISO trumpet curve requirements. The presentation of the information, e.g., the "Certificates of Participation", was designed to explain the results within the context of the ISO requirements to make the ILCs understandable and accessible to both technical and non-technical readers.

1.3. SCOPE

Phase I comprised an ILC for whole-body dosemeters (ILC-WB). The ILC-WB assessed the performance of personal dosimetry systems with integrating passive detectors for photon radiation, which are routinely employed to determine personal dose equivalent, $H_p(10)$ and/or $H_p(0.07)$, as surrogates for the exposure of the whole-body and the skin.. Reference irradiations were carried out in metrology laboratories for ionizing radiation, which are considered as internationally recognized Calibration and Measurement Capabilities (CMCs) by the International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM), according to the requirements of ISO 4037-1:2019 [5] and IEC 62387:2020 [6] in terms of $H_p(10)$ and $H_p(0.07)$. Radiation qualities, doses and angles of incidence were selected to emulate the field exposure conditions and to allow for an investigation of accuracy, linearity of response and reproducibility in the following ranges:

- Radiation quality: Gamma and X-radiation with mean energies from 33 keV to 662 keV
- Personal dose equivalent, $H_p(10)$ and $H_p(0.07)$: 0.3 mSv to 10 mSv
- Angle of incidence: ± 60°

Phase II comprised separate ILCs for extremity (ILC-EXT) and eye-lens (ILC-EYE) dosemeters. The ILC-EXT-EYE assessed the performance of personal dosimetry systems with integrating passive detectors for beta radiation, which are routinely employed to determine personal dose equivalent, $H_p(0.07)$ and/or $H_p(3)$, as surrogates for the exposure of extremities and the lens of the eye. Reference irradiations were carried out in accredited metrology laboratories for ionizing radiation, which are considered as internationally recognized CMCs by the BIPM, according to the requirements of ISO 6980-3:2023 [7] and IEC 62387:2020 [6] in terms of $H_p(0.07)$ and/or $H_p(3)$. Radiation qualities, doses and angles of incidence were selected to emulate the field exposure conditions and allow for an investigation of accuracy, linearity of response and reproducibility in the following ranges:

- Radiation quality: Beta-particle radiation with maximum energy of 2.274 MeV
- Personal dose equivalent, $H_p(0.07)$ and $H_p(3)$: 1.0 mSv to 10 mSv
- Angle of incidence: ± 45°

1.4. STRUCTURE

This publication contains descriptions of the ILC design and participating IMSs (Section 2); the methods employed for the distribution of the dosemeters between participating IMSs and irradiation laboratories (Section 3). The results of the ILCs are presented in Sections 4, 5 and 6, and conclusions in Section 7. The Appendix contains anonymised examples of the “Provisional Results and Analysis” and “Certificate of Participation”.

Organizer

IAEA Radiation Safety Technical Services Laboratory
International Atomic Energy Agency
E-mail: RSTSU.Contact-Point@iaea.org

The organizer was responsible for sponsoring, planning, organisation, and dosemeter logistics.

Co-ordinator

Andrew McWhan
Chartered Radiation Protection Professional
E-mail: ic.alps2023@charthouse.co.uk
The co-ordinator was responsible for ensuring confidentiality during the reporting phase and drafting the final analysis and reports.

Irradiating Laboratories

ILC-WB X-rays:	International Atomic Energy Agency, Austria
ILC-WB S-Cs:	Seibersdorf Laboratories, Austria
ILC-EXT $^{90}Sr/^{90}Y$:	Research Centre for Energy, Environment and Technology, Spain (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, CIEMAT)
ILC-EYE $^{90}Sr/^{90}Y$:	Physikalisch-Technische Bundesanstalt (PTB), Germany

2. DESIGN AND PARTICIPATING INDIVIDUAL MONITORING SERVICES

2.1. INTERLABORATORY COMPARISON PROCEDURE

IMSs were required to complete the application forms (see Appendix 1 and 2) which included instructions for preparation, labelling and dispatch of dosemeters. The forms also required basic details of the technical properties of the dosimetry system, including the method of dose calculation from the indicated value(s).

For ILC-WB, 30 dosemeters from each dosimetry system were required:

- 24 dosemeters for irradiation, and
- 6 background control/spare dosemeters.

For ILC-EXT-EYE, 22 dosemeters from each dosimetry system were required:

- 14 dosemeters for irradiation, and
- 8 background control/spare dosemeters.

All dosemeters were sent by the IMS to the organizer who forwarded the dosemeters to the irradiation laboratories.

After irradiation in accordance with the irradiation plans outlined in Section 3, the irradiation laboratories sent the dosemeters to the organizer and the reference dose information to the co-ordinator. The organizer then returned the dosemeters to the IMSs and the co-ordinator sent IMSs details of dosemeters that were not irradiated and could be used for subtraction of background and transit dose. After evaluation, the IMSs reported their results in terms of $H_p(10)$ and $H_p(0.07)$ to the co-ordinator using a standardized form.

After receiving the results, the co-ordinator calculated the value of the response, R, for each dosemeter reading by dividing the participant's result, G, by the reference dose given by the irradiating laboratory, H_{ref}:

$$R = \frac{G}{H_{ref}}$$

The co-ordinator then sent each IMS a report (see example presented in the Appendix). The IMSs were allowed two weeks to check and confirm their results, and they had the opportunity to add any comments.

After the two-week period for comment the Certificates of Participation (see example presented in the Appendix) were signed by the co-ordinator and the organizer and sent by email to the participants along with a copy of the formal irradiation reports issued by the irradiating laboratories.

2.2. DESIGN

ILC-WB and ILC-EXT-EYE were designed to meet the ISO 14146:2018 standard [4]. The performance limits set by ISO 14146 were also adopted for the analysis of the ILC results:

$$0.71 \cdot \left(1 - \frac{2H_0/1.33}{H_0/1.33 + H_{ref}}\right) \leq R \leq 1.67 \cdot \left(1 + \frac{H_0}{4H_0 + H_{ref}}\right)$$

R is the (relative) response, i.e., the ratio between the measured dose reported by the IMS and the reference dose, H_{ref} is the conventional quantity value (reference dose) and H_0 is the “lower dose limit below which irradiations should not be performed”:

- H_0 = 0.1 mSv for whole-body dosemeters measuring $H_p(10)$ and $H_p(0.07)$;
- H_0 = 1.0 mSv for extremity dosemeters measuring $H_p(0.07)$; and
- H_0 = 0.3 mSv for eye-lens dosemeters measuring $H_p(3)$.

The organizing authority, i.e., the IAEA Radiation Safety Technical Services Laboratory, arranged the basic schedule and irradiation plan but the actual doses were set by the Irradiation Laboratories with details sent in-confidence to the co-ordinator. After dosemeter evaluation the IMS sent the results to the co-ordinator who issued draft reports to each IMS showing *R* (reported value/reference dose). There is no direct contact between the IMS and the Irradiation Laboratories. The co-ordinator ensures confidentiality of the reference dose information until after all the participating IMS have evaluated the dosemeters and issued the results.

For the analysis of the results in this report, any result exceeding the above performance limits was to be considered as an outlier. ISO 14146:2018 allows a maximum of one-tenth of the irradiated dosemeters to exceed these limits. This criterion individually applies to each participant in the ILC.

2.3. TRUMPET CURVE EXPLANATION

The accuracy of dosemeters is significantly reduced at low doses because of the technical limits of all the various dosimetry systems. The ISO standards recognise these technical limitations. To meet the ISO standards, dosemeters must be able to measure doses to an accuracy within the limits set by the performance limits which are commonly referred to as “trumpet curves” because of their shape. It can be seen from the graphical representation of the above equation (Figure 1) that the standards are more lenient at the lower dose range as the “trumpet” width increases. The abscissa shows the reference dose, i.e., the dose given to the dosemeters by the irradiating laboratory, and the ordinate shows the response ratio of the dose reported by the IMS to the reference dose.

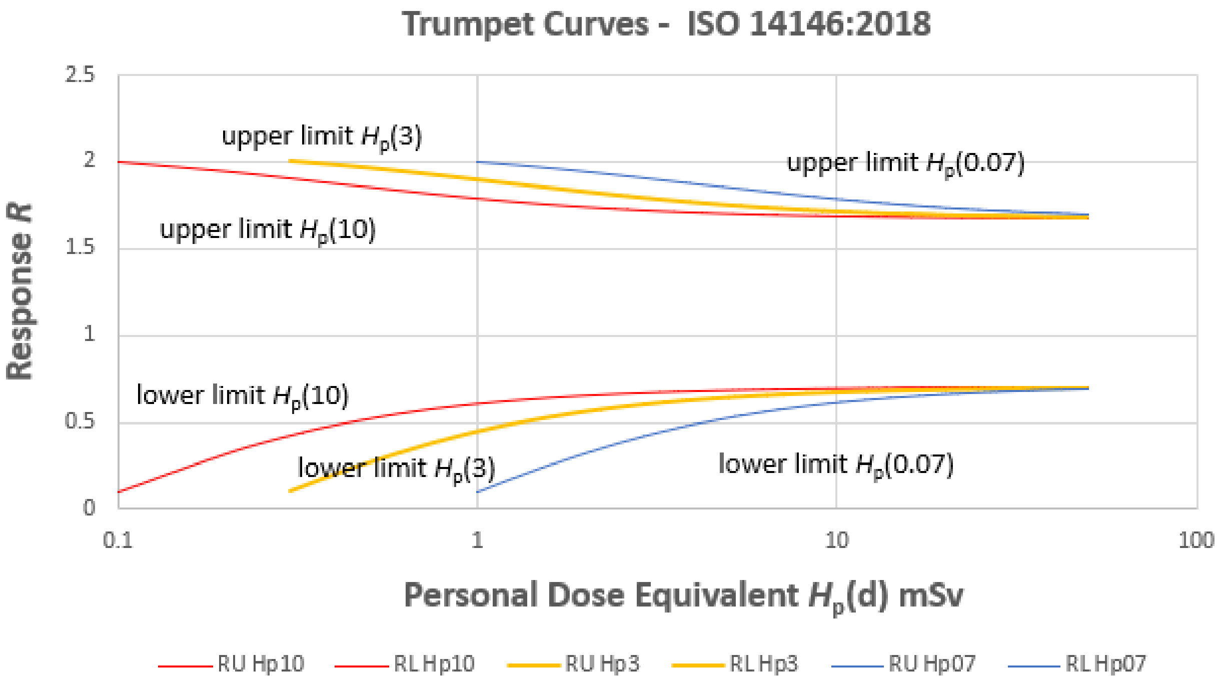


Figure 1: ISO 14146 trumpet curve for $H_p(10)$, $H_p(0.07)$ and $H_p(3)$.

Note: All irradiations were carried out for sets of two or four dosemeters for each reference dose value. Each dosemeter within a set for the reference dose value is plotted with a different colour but where *R* values for a given reference dose are close, they may not be visible separately on the graphs.

2.4. PARTICIPATING INDIVIDUAL MONITORING SERVICES

Chiyoda Technol Corporation
Personal Radiation Monitoring Service Business Headquarters
Radiation Monitoring Center
3522, Onuki-cho, Oarai, Higashi-Ibaraki, Ibaraki, 311-1311 Japan

International Atomic Energy Agency
Radiation Safety Technical Services Laboratory
Division of Radiation, Transport and Waste Safety
Vienna International Centre, PO Box 100, 1400 Vienna, Austria

Nagase Landauer Ltd
Dosimetry Center
Technical Division
Block C22-1, Suwa, Tsukuba, Ibaraki, 300-2686 Japan

Chiyoda Technol Corporation and Nagase Landauer Ltd have been contracted by TEPCO for the assessment of external radiation exposure of workers involved in handling ALPS-treated water.

As the IAEA Radiation Safety Technical Services Laboratory does not routinely employ a dedicated eye-lens dosimetry system, they did not participate in ILC-EYE.

2.5. CONFIDENTIALITY OF DATA

The three participating IMSs were assigned codes S01, S02 and S03. All published reports only refer to these codes and the identities of the IMSs are protected.

2.6. UNCERTAINTIES

The uncertainties reported by the irradiating laboratories are shown in Sections 3.1 for ILC-WB, Section 3.2 for ILC-EXT, and Section 3.3 for ILC-EYE. The reported uncertainties were considered insignificant in terms of the overall results and, consequently, not included in the calculations for the "Certificates of Participation" or the analysis of the results.

2.7. CERTIFICATES OF PARTICIPATION

An anonymized example of a Certificate of Participation is presented in the Appendix. These certificates were designed as stand-alone documents to be understandable and accessible to technical and non-technical readers. The results were presented in graphical and numerical format in the context of the relevant trumpet curves and ISO 14146 performance limits (see numerical sample example below):

IMS $H_p(10)$ = value (mSv) reported by IMS			Ref $H_p(10)$ = value (mSv) reported by irradiating lab				
Dosemeter ID	Quality	IMS $H_p(10)$ mSv	Ref $H_p(10)$ mSv	R IMS/Ref	ISO upper limit	ISO lower limit	Outlier
S01-ILC-WB-58	S-Cs	14.05	13.40	1.05 *R1*	1.68	0.70	no
S01-ILC-WB-63	S-Cs	14.09	13.40	1.05 *R2*	1.68	0.70	no

Notes were included to explain the graphs, irradiation uncertainties and ISO 14146 approval criterion:

Note1: *R* IMS/Ref *R* (either *R1, R2, R3 or R4*) for each dosemeter irradiation is plotted against dose $H_p(10)$ [mSv] in the graph below. Where *R* values for a given dose are very close, they may not be visible separately on the graph.
Note 2: X-ray uncertainties: The SSDL reported that the relative uncertainties (k = 2) for reference irradiations was 4.2% as determined in accordance with JCGM 100-2008.
Note 3: S-Cs uncertainties: The SSDL reported that the expanded uncertainty (k = 2) was 5% as determined in accordance with European co-operation of Accreditation Publication EA/4/02 M:2022.
Note 4: ISO 14146:2018 approval criterion: *A maximum of 1/10 (i.e., 2 in this sample) of the irradiated dosemeters may exceed the performance limits.* **It can be seen from the reported *R* values and the graph that all dosemeters have met the ISO 14146 approval criterion for all the test radiation qualities and angles of incidence.**

The final page included a summary of the procedure and performance criteria including an explanation of the trumpet curves.

3. IRRADIATION PLANS

To prevent against cross-comparison of measurement results before the reference values were released, the irradiation plans specified ranges of doses and tasked the irradiating laboratories to select the reference dose applied to a set of dosemeters from a particular IMS from within that range. Consequently, reference doses could vary among participating IMSs.

To obtain clear reference values in terms of personal dose equivalent, irradiations were carried out on the following phantoms:

- slab phantom of outer dimensions 30 cm × 30 cm × 15 cm with polymethyl methacrylate (PMMA) walls (front wall 2.5 mm thick, other walls 10 mm thick) filled with water to approximate the human torso for irradiation of whole-body dosemeters in accordance with ISO 4037-3:2019 [8];
- rod phantom composed of a PMMA cylinder of 19 mm diameter and 300 mm length to approximate a finger for irradiation of extremity dosemeters in accordance with ISO 6980-3:2023 [9]; and/or
- PMMA plate phantom of dimensions 20 cm × 20 cm × 2 cm for beta-particle irradiation of eye-lens dosemeters in accordance with ISO 6980-3:2023 [9, 10].

3.1. WHOLE-BODY DOSIMETRY

Irradiating Laboratory X-rays:
International Atomic Energy Agency (IAEA), Austria

Radiation quality:	N-series X-ray radiation (in accordance with ISO 4037-1:2019)
Phantom:	ISO slab phantom
Reference point:	Reference point of dosemeter (4 mm (S01, S02) and 5 mm (S03) from back)
Expanded uncertainty (*k* = 2):	4.2% (in accordance with JCGM 100-2008)

Table 1: Whole-body dosemeter irradiation plan – X-rays.

Radiation quality	Angle of incidence	Dose range	Dosemeters per IMS
N-40	0°	1~5 mSv	4
N-40	H +60°	1~5 mSv	2
N-100	0°	1~5 mSv	2
N-200	0°	1~5 mSv	2

Irradiating Laboratory S-Cs:

Seibersdorf Laboratories (SL), Austria

Radiation quality:	Gamma radiation S-Cs (^{137}Cs, in accordance with ISO 4037-1:2019)
Phantom:	ISO slab phantom
Reference point:	At front surface centre of phantom
Expanded uncertainty (*k* = 2):	5% (in accordance with EA/4/02 M:2022)

Table 2. Whole-body dosemeter irradiation plan – S-Cs.

Radiation quality	Angle of incidence	Dose range	Dosemeters per IMS
S-Cs	0°	1~2 mSv	4
S-Cs	H +60°	1~5 mSv	4
S-Cs	0°	2~5 mSv	2
S-Cs	0°	10~15 mSv	2

3.2. EXTREMITY DOSIMETRY

Irradiating Laboratory:

Research Centre for Energy, Environment and Technology (CIEMAT), Spain

Radiation quality:	$^{90}Sr/^{90}Y$ (in accordance with ISO 6980-1:2023)
Phantom:	ISO rod phantom
Reference point:	Reference point of dosemeter (4 mm from back)
Expanded uncertainty (*k* = 2):	4.5% at 0°, 5.1% at +45° (in accordance with JCGM 100:2008)

Table 3. Extremity dosemeter irradiation plan – $^{90}Sr/^{90}Y$.

Radiation quality	Angle of incidence	Dose range	Dosemeters per IMS
$^{90}Sr/^{90}Y$	0°	1~2 mSv	4
$^{90}Sr/^{90}Y$	0°	3~5 mSv	4
$^{90}Sr/^{90}Y$	0°	6~10 mSv	4
$^{90}Sr/^{90}Y$	H +45°	3~5 mSv	2

3.3. EYE-LENS DOSIMETRY

Irradiating Laboratory:
Physikalisch-Technische Bundesanstalt (PTB), Germany

Radiation quality:	$^{90}Sr/^{90}Y$ according to ISO 6980-1:2023
Phantom:	PMMA plate phantom
Reference point:	Reference point of dosemeter (4 mm from back)
Expanded uncertainty (k = 2):	4.4% at 0°, 5.8% at +45° (in accordance with JCGM 100:2008)

Table 4. Eye-lens dosemeter irradiation plan – $^{90}Sr/^{90}Y$.

Radiation quality	Angle of incidence	Dose range	Dosemeters per IMS
$^{90}Sr/^{90}Y$	0°	1~2 mSv	4
$^{90}Sr/^{90}Y$	0°	3~5 mSv	4
$^{90}Sr/^{90}Y$	0°	6~10 mSv	4
$^{90}Sr/^{90}Y$	H +45°	3~5 mSv	2

3.4. TOTAL NUMBER OF IRRADIATIONS

Table 5. Summary of total numbers of irradiations.

ILC	Number of dosemeters per IMS	Total number of dosemeters
ILC-WB	22	66
ILC-EXT	14	42
ILC-EYE	14	28
Total	50	136

3.5. BACKGROUND AND TRANSIT DOSE CONTROL

It can be seen in Table 6 that there had been no significant transit dose and that there was no impact on the quality of the dosemeter assessments even at the lower end of the dose ranges for the ILC-WB, ILC-EXT and ILC-EYE. In total, four whole-body and four extremity dosemeters had been wrongly irradiated and had to be replaced from the pool of spare dosemeters.

Table 6. Background and transit dose.

ILC	Number of transit doses reported	Mean transit dose	Transit dose range
ILC-WB	52	0.11 mSv	0.06~0.15 mSv
ILC-EXT	20	0.21 mSv	0.14~0.26 mSv
ILC-EYE	16	0.15 mSv	0.15~0.20 mSv
Total	88	0.16 mSv	0.06~0.26 mSv

4. RESULTS AND DISCUSSION: WHOLE-BODY DOSIMETRY

4.1. RELATIVE RESPONSE: TRUMPET CURVES

Response, *R*, for each dosemeter irradiation is plotted against reference dose, $H_p(10)$ and $H_p(0.07)$, and the ISO trumpet curves for each IMS in Figures 2 to 7. Where *R* values for a given reference dose are very close, they may not be visible separately on the graph. ***It can be seen that all the results for whole-body dosimetry are well within the ISO performance limits for all irradiations. Figure 8 shows that the distribution of response for all irradiations is also satisfactory.***

Figure 2: Dosemeter response with respect to reference dose to the whole body for participant S01. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid red lines.

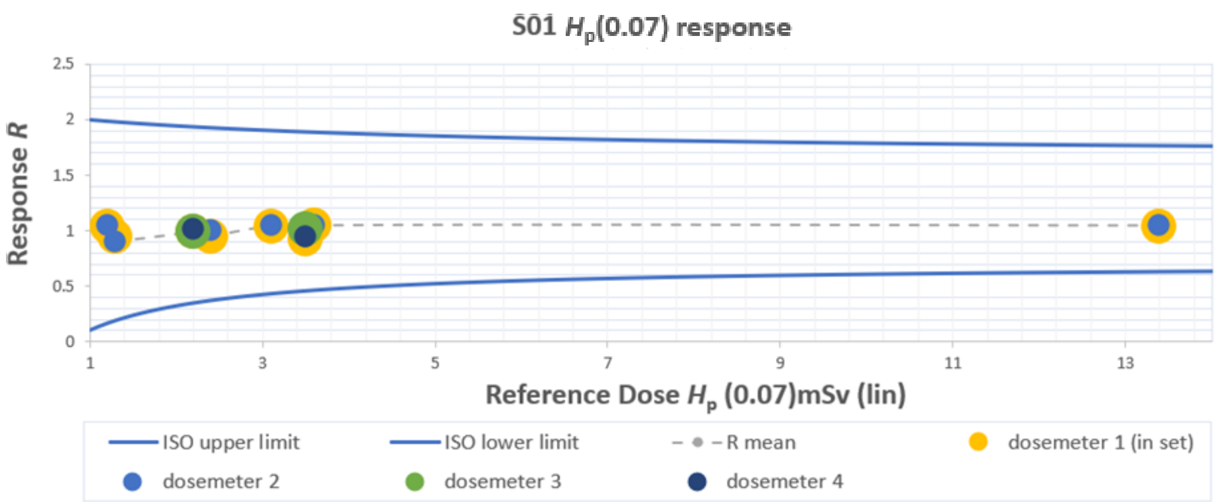


Figure 3: Dosemeter response with respect to reference dose to the skin for participant S01. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid blue lines.

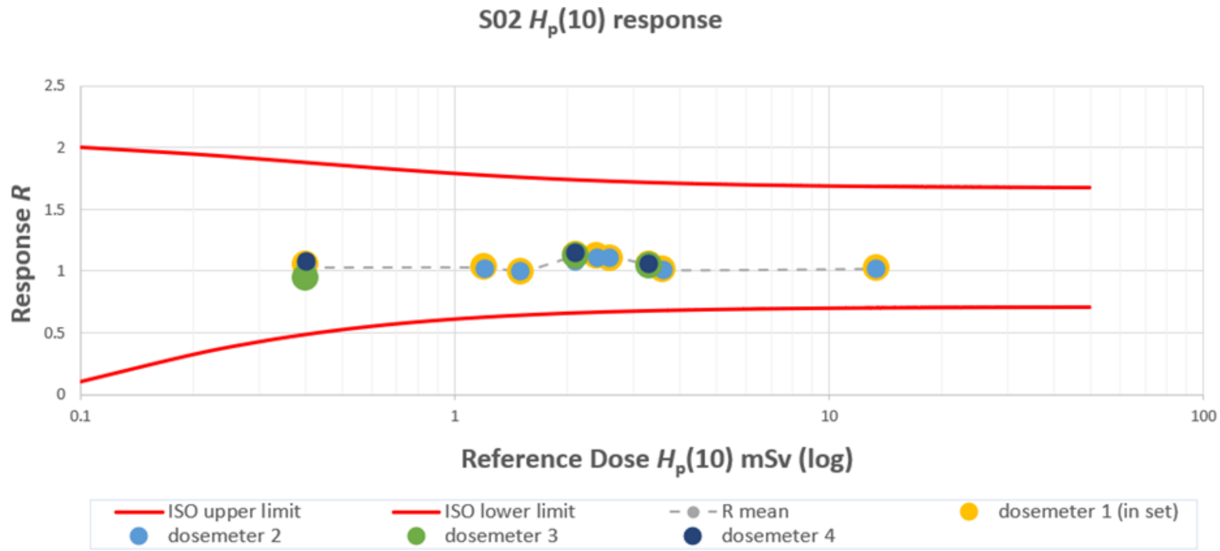


Figure 4: Dosemeter response with respect to reference dose to the whole body for participant S02. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid red lines.

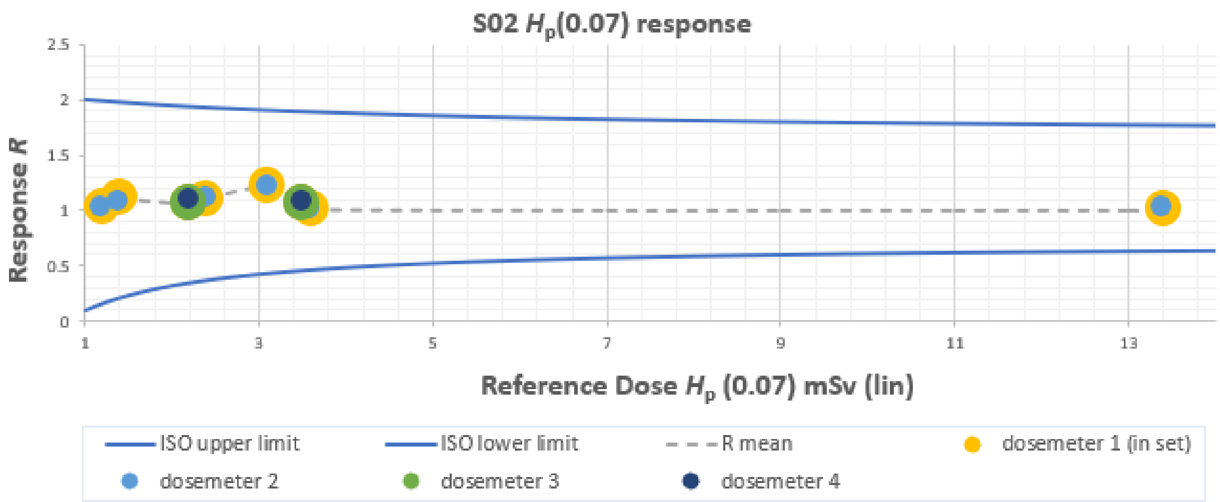


Figure 5: Dosemeter response with respect to reference dose to the skin for participant S02. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid blue lines.

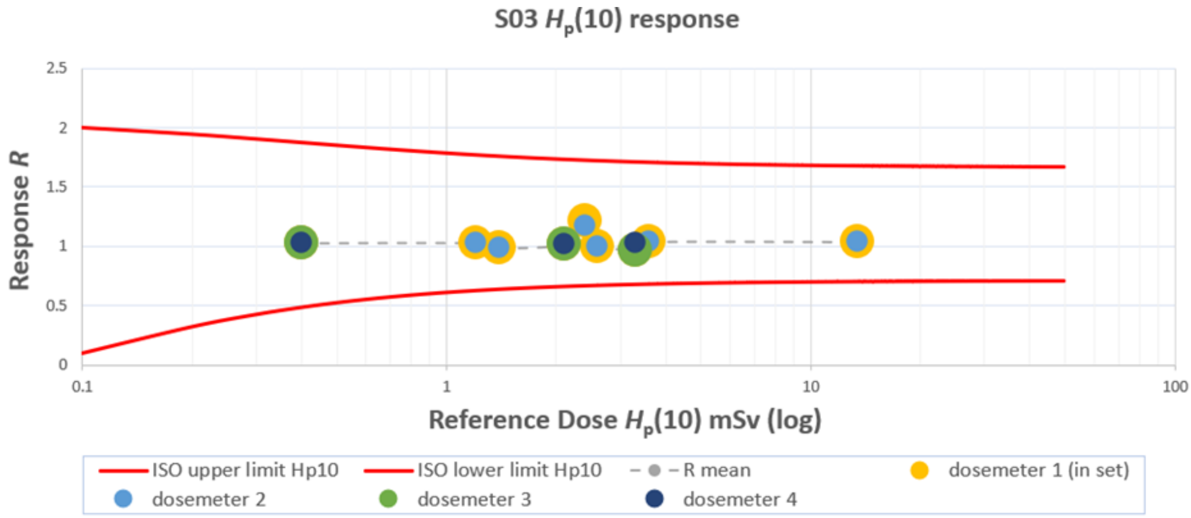


Figure 6: Dosemeter response with respect to reference dose to the whole body for participant S03. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid red lines.

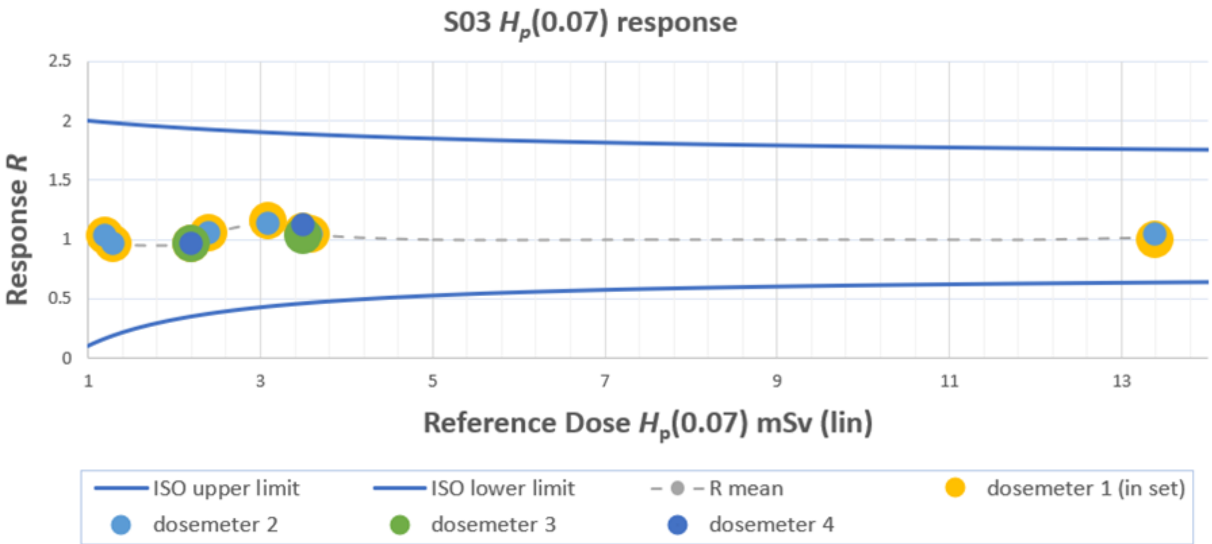


Figure 7: Dosemeter response with respect to reference dose to the skin for participant S03. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid blue lines.

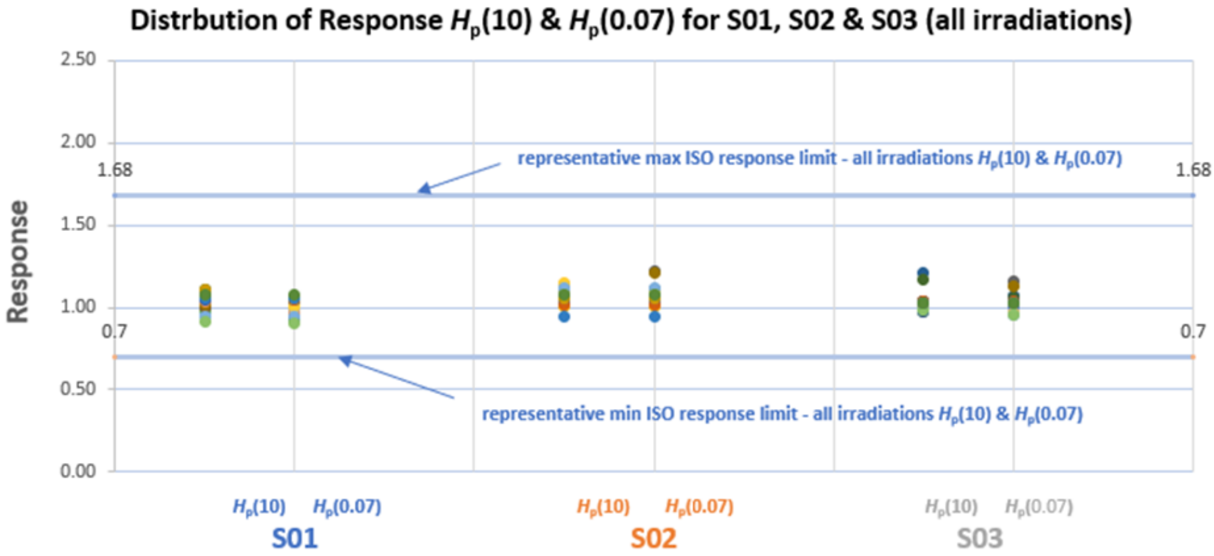


Figure 8: Distribution of response in terms of $H_p(10)$ and $H_p(0.07)$ for participants S01, S02 and S03.

Table 7. Whole-body dosemeter response for all irradiations.

Quality (dosem.)	Reference dose[1] (mSv)		S01 Response *R*			S02 Response *R*			S03 Response *R*		
			Mean	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
S-Cs (2)	$H_p(10)$	13.40	**1.05**	1.05	1.05	**1.02**	1.02	1.02	**1.04**	1.04	1.04
	$H_p(0.07)$	13.40	**1.05**	1.05	1.04	**1.02**	1.02	1.02	**1.02**	1.04	1.00
S-Cs (2)	$H_p(10)$	3.60	**1.06**	1.06	1.05	**1.01**	1.01	1.01	**1.04**	1.04	1.04
	$H_p(0.07)$	3.60	**1.05**	1.05	1.05	**1.01**	1.01	1.01	**1.04**	1.04	1.04
N-40 (4)	$H_p(10)$	3.33	**1.00**	1.01	0.98	**1.05**	1.06	1.04	**0.99**	1.03	0.97
	$H_p(0.07)$	3.52	**0.96**	1.01	0.92	**1.07**	1.08	1.07	**1.07**	1.12	1.03
N-100 (2)	$H_p(10)$	2.64	**1.02**	1.02	1.01	**1.11**	1.11	1.10	**1.00**	1.00	1.00
	$H_p(0.07)$	2.41	**0.98**	1.00	0.95	**1.11**	1.11	1.10	**1.05**	1.05	1.05
N-40 60° (2)	$H_p(10)$	2.43	**1.10**	1.11	1.08	**1.12**	1.12	1.11	**1.19**	1.21	1.17
	$H_p(0.07)$	3.14	**1.04**	1.05	1.03	**1.22**	1.22	1.21	**1.15**	1.16	1.13
S-Cs 60° (4)	$H_p(10)$	2.10	**1.06**	1.07	1.03	**1.12**	1.15	1.08	**1.02**	1.02	1.02
	$H_p(0.07)$	2.22	**0.99**	1.01	0.96	**1.06**	1.09	1.02	**0.96**	0.96	0.96
N-200 (2)	$H_p(10)$	1.39	**0.93**	0.94	0.91	**1.1**	1.12	1.08	**0.99**	0.99	0.99
	$H_p(0.07)$	1.33	**0.92**	0.94	0.90	**1.10**	1.12	1.07	**0.96**	0.96	0.96
S-Cs (2)	$H_p(10)$	1.20	**1.06**	1.07	1.04	**1.03**	1.03	1.02	**1.03**	1.03	1.03
	$H_p(0.07)$	1.20	**1.05**	1.05	1.04	**1.03**	1.03	1.02	**1.03**	1.03	1.03
S-Cs (4)	$H_p(10)$	0.38	**1.08**	1.11	1.05	**1.03**	1.08	0.95	**1.03**	1.03	1.03
	$H_p(0.07)$	0.38	**1.06**	1.08	1.05	**1.03**	1.08	0.95	**1.03**	1.03	1.03

[1] X-ray dose was varied. This table shows mean value for all 3 IMSs.

4.2. LINEARITY

Figures 9 to 20 and Table 8 show linearity of whole-body dosemeter responses in terms of gradient and R^2. ***It can be seen that the results for the irradiations performed at normal incidence are all satisfactory, with all values for gradient and R^2 close to 1.***

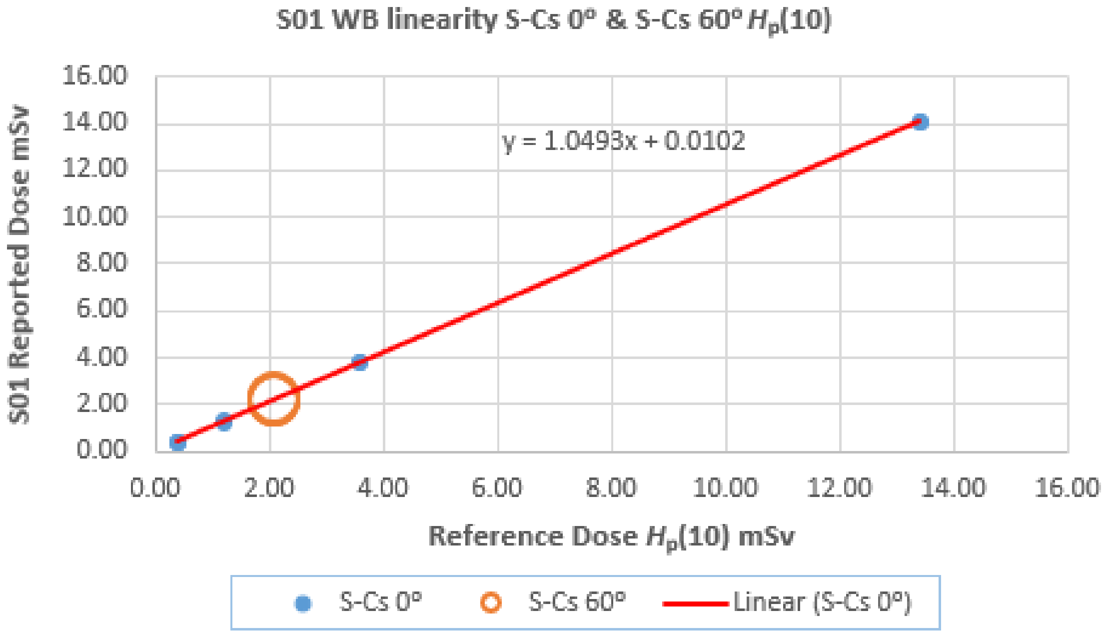


Figure 9: $H_p(10)$ linearity and angular response to S-Cs for participant S01.

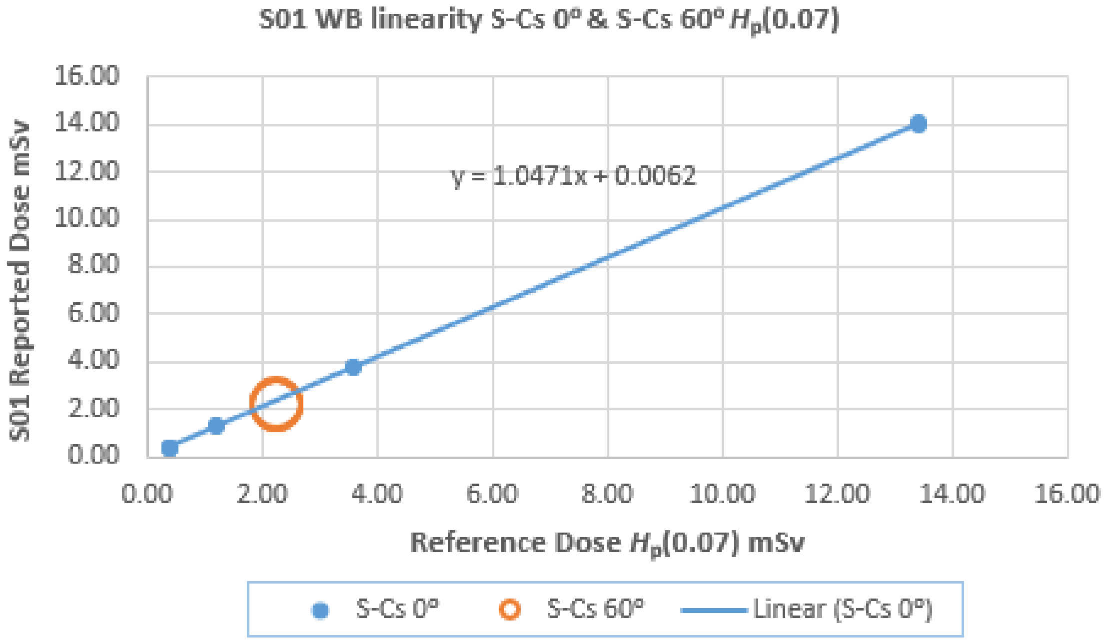


Figure 10: $H_p(0.07)$ linearity and angular response to S-Cs for participant S01.

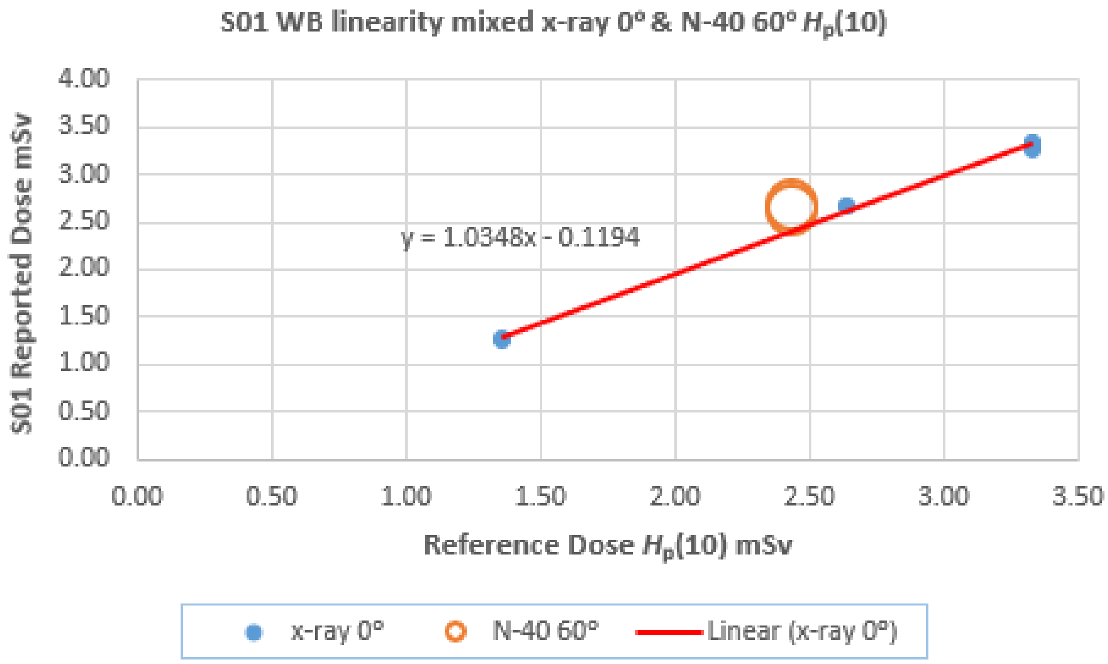


Figure 11: $H_p(10)$ linearity and angular response to X-rays for participant S01.

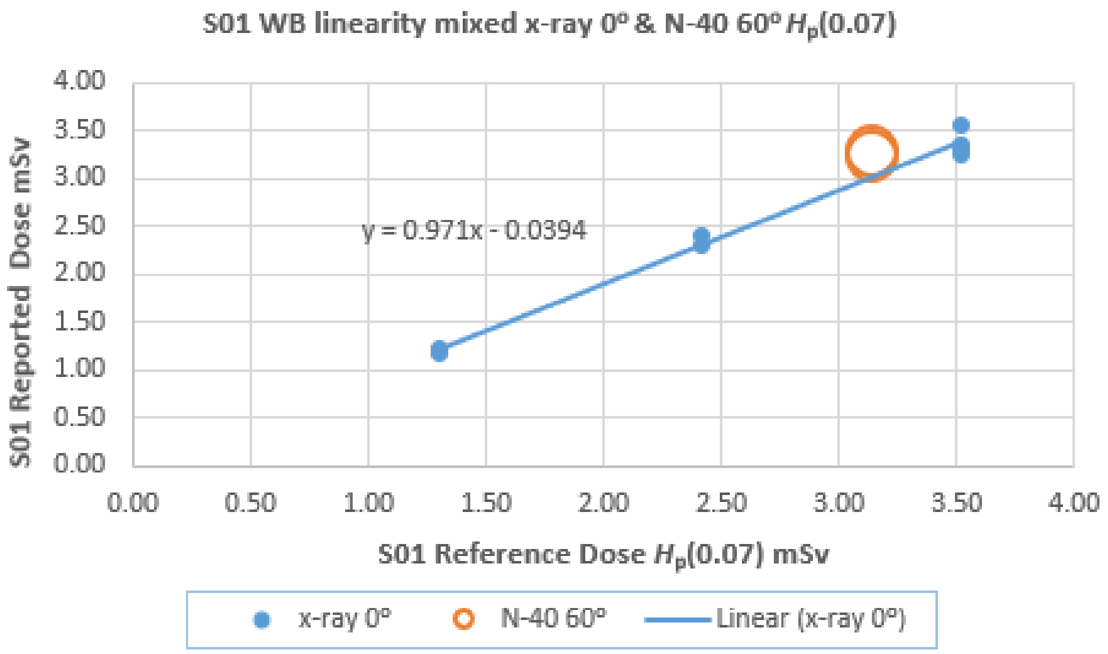


Figure 12: $H_p(0.07)$ linearity and angular response to X-rays for participant S01.

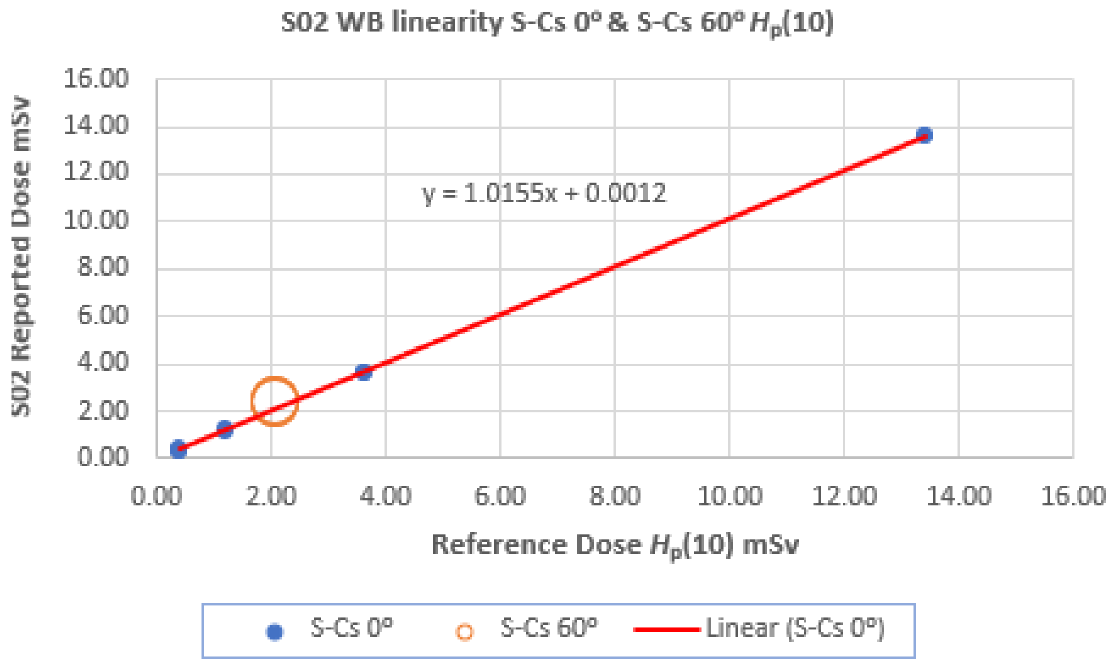


Figure 13: $H_p(10)$ linearity and angular response to S-Cs for participant S02.

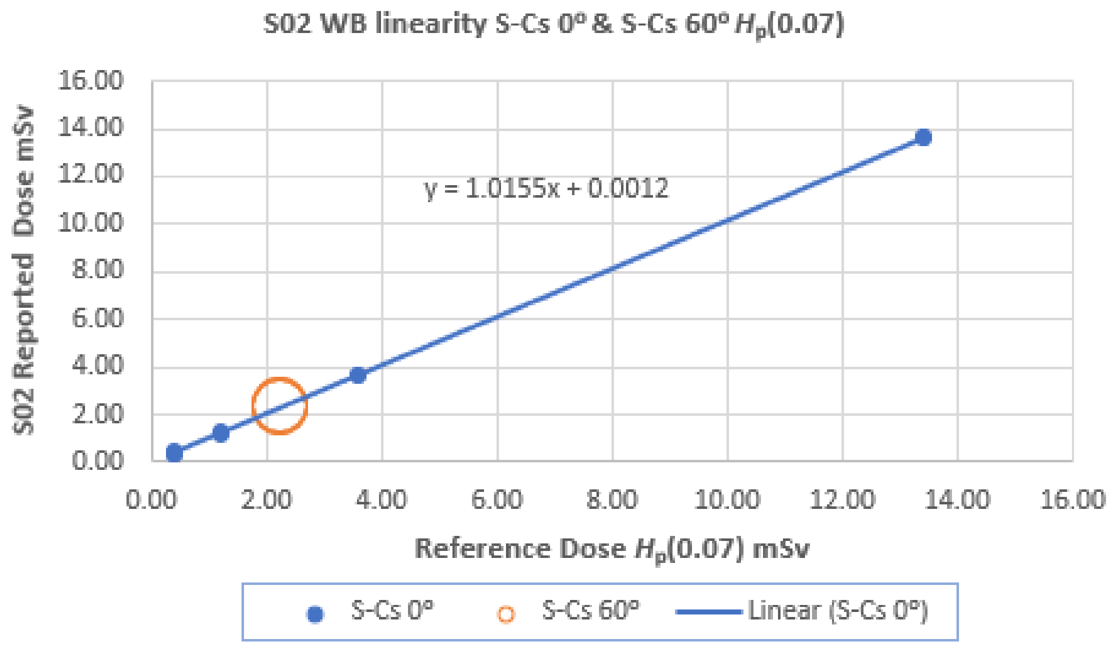


Figure 14: $H_p(0.07)$ linearity and angular response to S-Cs for participant S02.

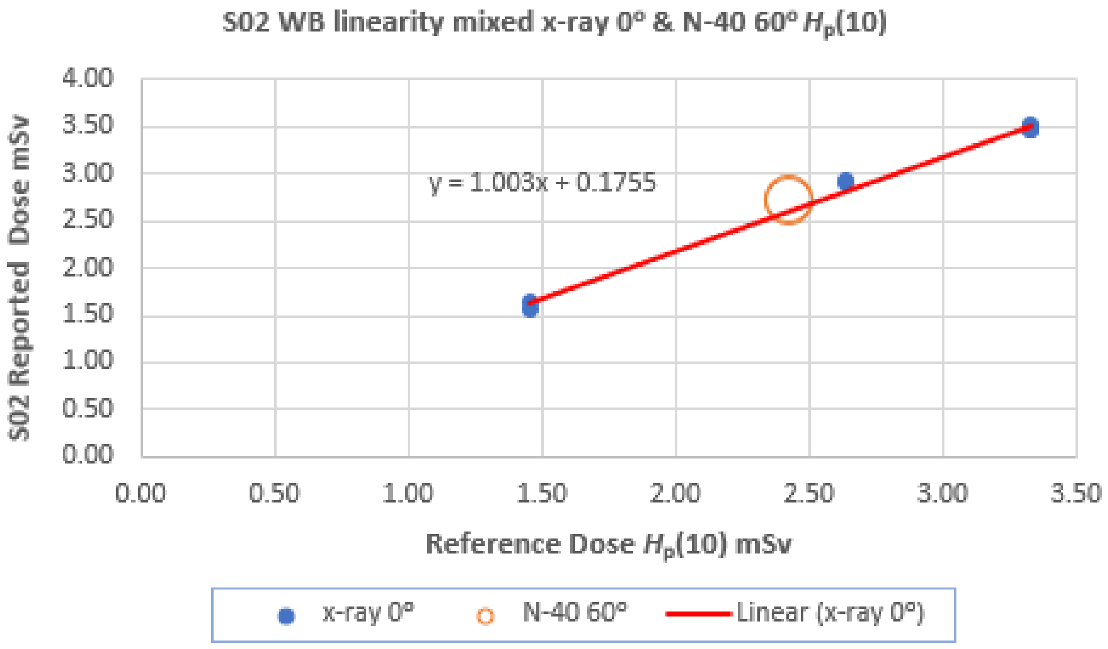


Figure 15: $H_p(10)$ linearity and angular response to X-rays for participant S02.

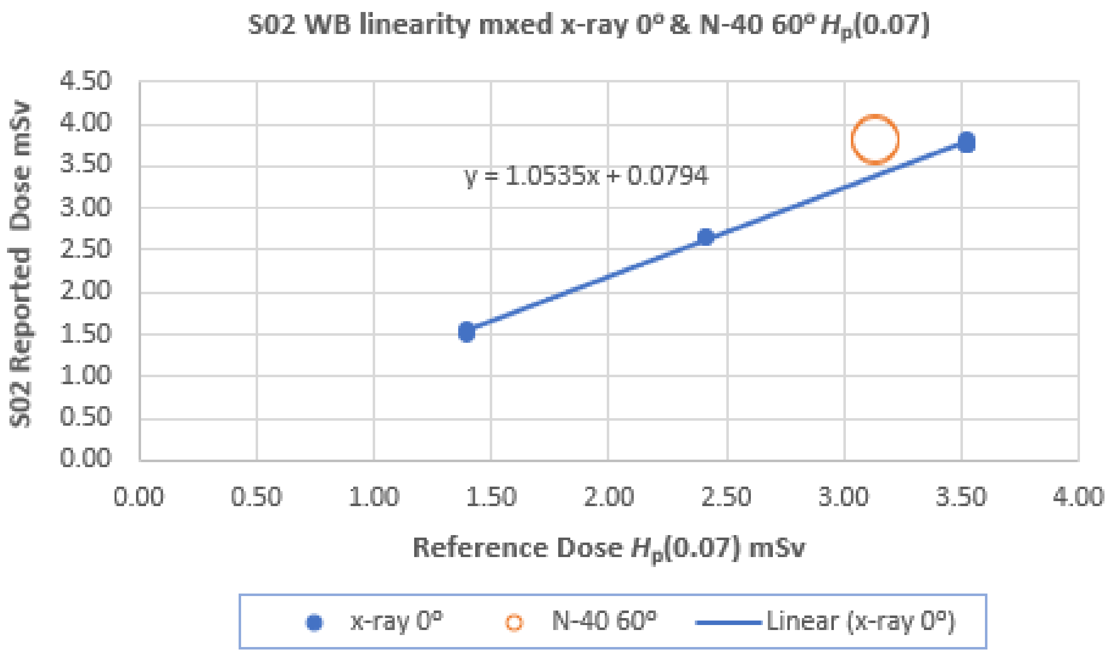


Figure 16: $H_p(0.07)$ linearity and angular response to X-rays for participant S02.

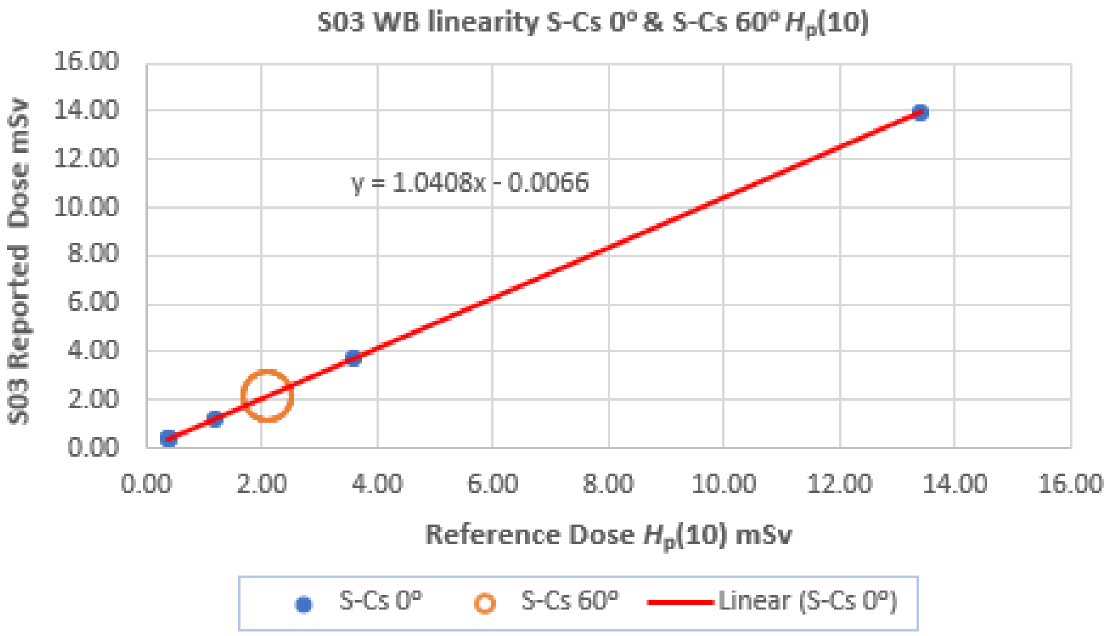


Figure 17: $H_p(10)$ linearity and angular response to S-Cs for participant S03.

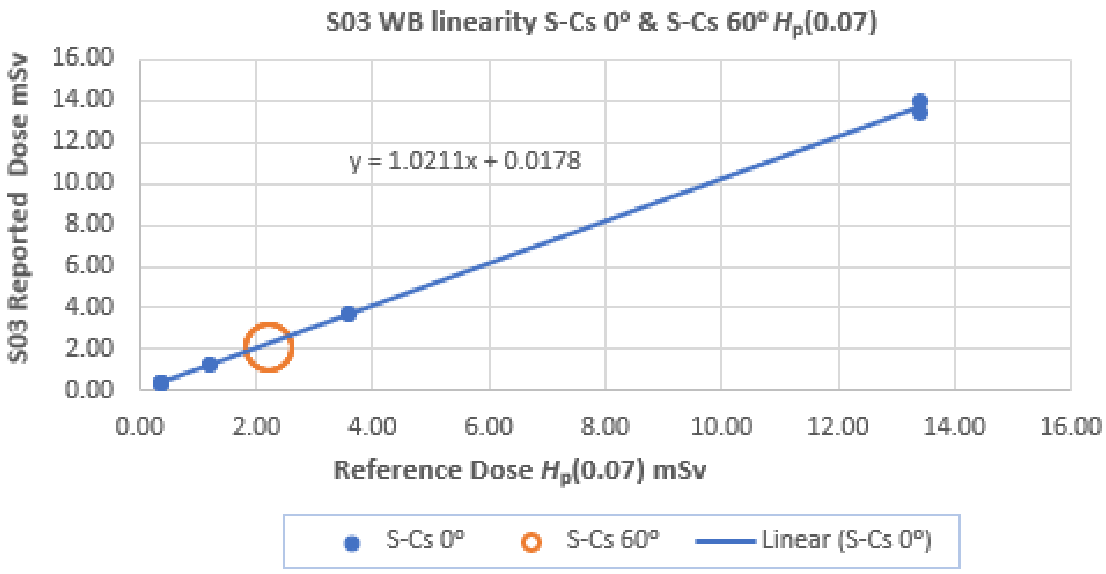


Figure 18: $H_p(0.07)$ linearity and angular response to S-Cs for participant S03.

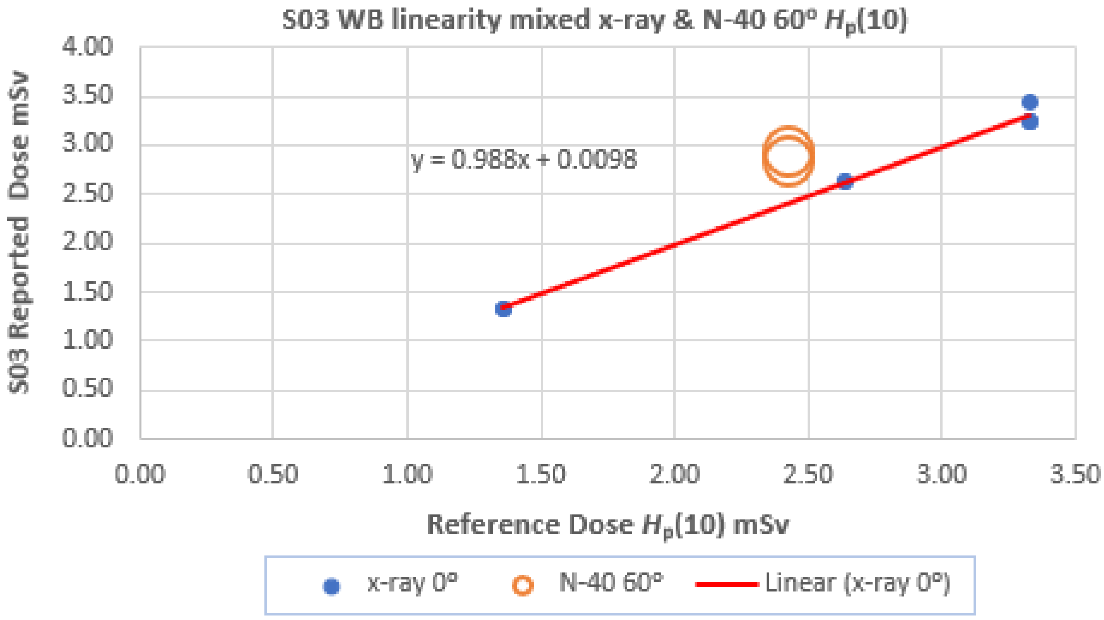


Figure 19: $H_p(10)$ linearity and angular response to X-rays for participant S03.

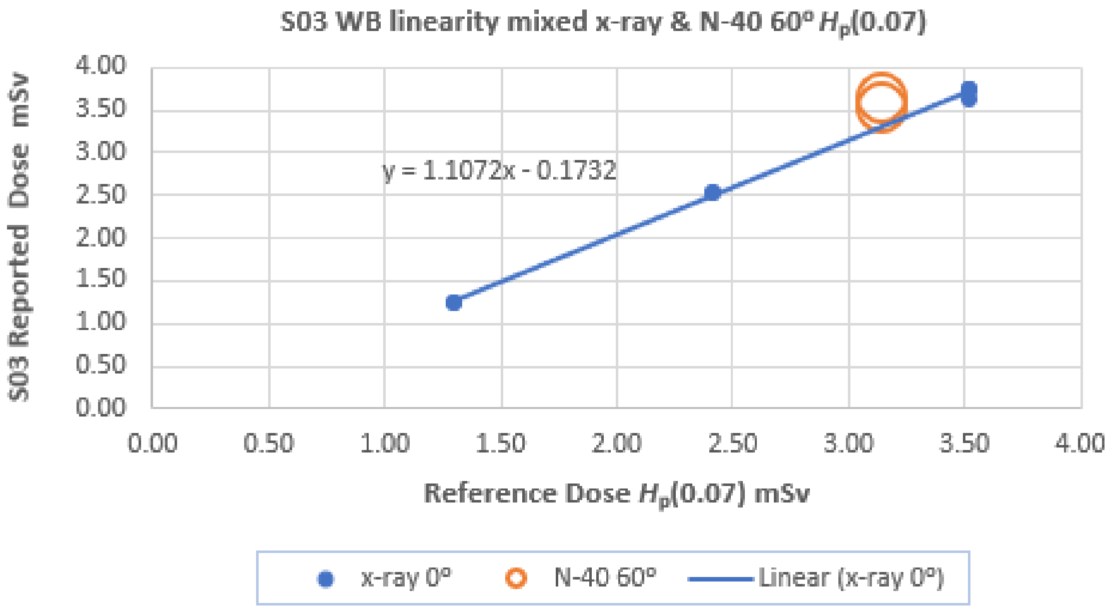


Figure 20: $H_p(0.07)$ linearity and angular response to X-rays for participant S03.

Table 8. Linearity of whole-body dosemeter response to S-Cs and X-rays.

Quality	Reference dose range (mSv)		S01	S02	S03
			Response: Gradient and R^2	Response: Gradient and R^2	Response: Gradient and R^2
S-Cs	0.38~13.40	$H_p(10)$	$y = 1.0493\,x + 0.0102$ $R^2 = 0.999$	$y = 1.0155\,x + 0.0012$ $R^2 = 0.999$	$y = 1.0408\,x - 0.0066$ $R^2 = 0.999$
		$H_p(0.07)$	$y = 1.0471\,x + 0.0062$ $R^2 = 0.999$	$y = 1.0155\,x + 0.0012$ $R^2 = 0.999$	$y = 1.0211\,x + 0.0178$ $R^2 = 0.999$
N-40 N-100 N-200	1.36~3.33	$H_p(10)$	$y = 1.0348\,x - 0.1194$ $R^2 = 0.997$	$y = 1.003\,x + 0.1755$ $R^2 = 0.994$	$y = 0.9880\,x + 0.0098$ $R^2 = 0.994$
		$H_p(0.07)$	$y = 0.9710\,x - 0.0394$ $R^2 = 0.989$	$y = 1.0535\,x + 0.0794$ $R^2 = 0.999$	$y = 1.1072\,x - 0.1732$ $R^2 = 0.998$

4.3. ANGULAR RESPONSE

It can be seen in Figures 9 to 20 and Table 9 that angular response is satisfactory, with a maximum over response to $H_p(10)$ from S-Cs (60°) of 1.12 and to $H_p(0.07)$ from N-40 (60°) of 1.22.

Table 9. Whole-body dosemeter angular response to S-Co (60°) and X-rays (60°).

Quality (dosem.)	Reference dose (mSv)		S01	S02	S03
			Mean response *R*	Mean response *R*	Mean response *R*
S-Cs 60° (4)	$H_p(10)$	2.10	1.06	1.12	1.02
	$H_p(0.07)$	2.22	0.99	1.06	0.96
N-40 60° (2)	$H_p(10)$	2.43	1.10	1.12	1.19
	$H_p(0.07)$	3.14	1.04	1.22	1.15

4.4. REPRODUCIBILITY

Table 10 shows reproducibility based on N-40 (0°) and S-Cs (60°) irradiations. ***The results are satisfactory, with all values of response, R, and the calculated coefficients of variation, CoV, less than 3.5%.***

Table 10. Reproducibility of whole-body dosemeter response.

Quality (dosem.)	Reference dose[1] (mSv)		S01			S02			S03		
			Response *R*			Response *R*			Response *R*		
			Mean	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
N-40 0° (4)	$H_p(10)$ $H_p(0.07)$	3.33 3.52	**1.00** **0.96**	1.01 1.01	0.98 0.92	**1.05** **1.07**	1.06 1.08	1.04 1.07	**0.99** **1.07**	1.03 1.12	0.97 1.03
CoV	$H_p(10)$ $H_p(0.07)$		1.1% 3.5%			0.8% 0.0%			0.0% 3.1%		
S-Cs 60° (4)	$H_p(10)$ $H_p(0.07)$	2.10 2.22	**1.06** **0.99**	1.07 1.01	1.03 0.96	**1.12** **1.06**	1.15 1.09	1.08 1.02	**1.02** **0.96**	– –	– –
CoV	$H_p(10)$ $H_p(0.07)$		1.4% 1.8%			2.3% 2.4%			0.0% 0.0%		

4.5. OUTLIERS

There were no outliers.

5. RESULTS AND DISCUSSION: EXTREMITY DOSIMETRY

5.1. RELATIVE RESPONSE: TRUMPET CURVES

Response, *R*, for each dosemeter irradiation is plotted against reference dose, $H_p(0.07)$, and the ISO trumpet curves for each IMS in Figures 21 to 23. Where *R* values for a given reference dose are very close, they may not be visible separately on the graph. ***All the results for extremity dosimetry are well within the performance limits for all irradiations. While still satisfactory, the response, R, dips close to the lower performance limit for all IMSs for the 5 mSv irradiations at 45° incidence.***

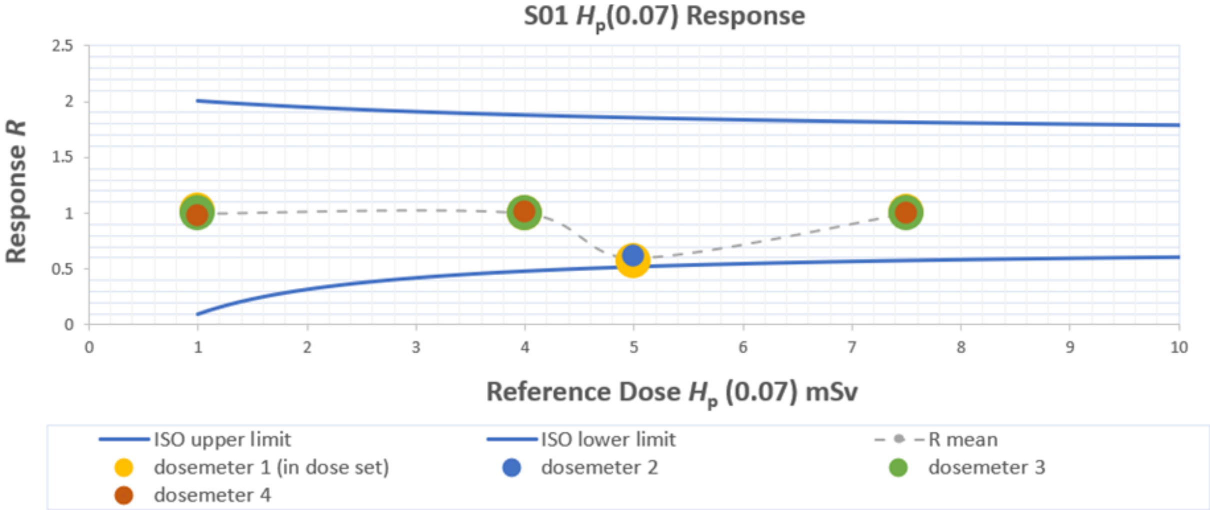


Figure 21: Dosemeter response with respect to reference dose to extremity for participant S01. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid blue lines.

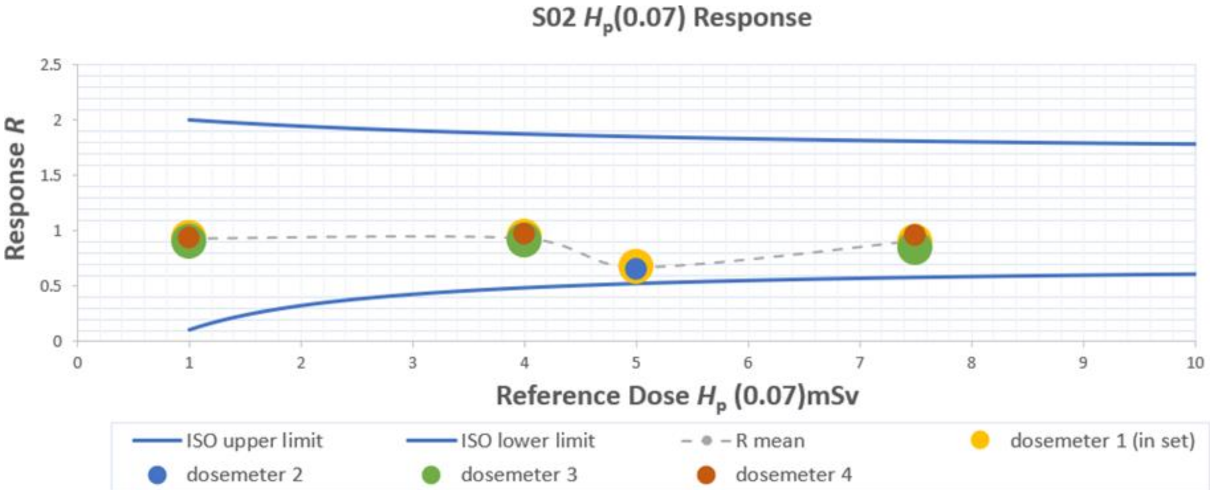


Figure 22: Dosemeter response with respect to reference dose to extremity for participant S02. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid blue lines.

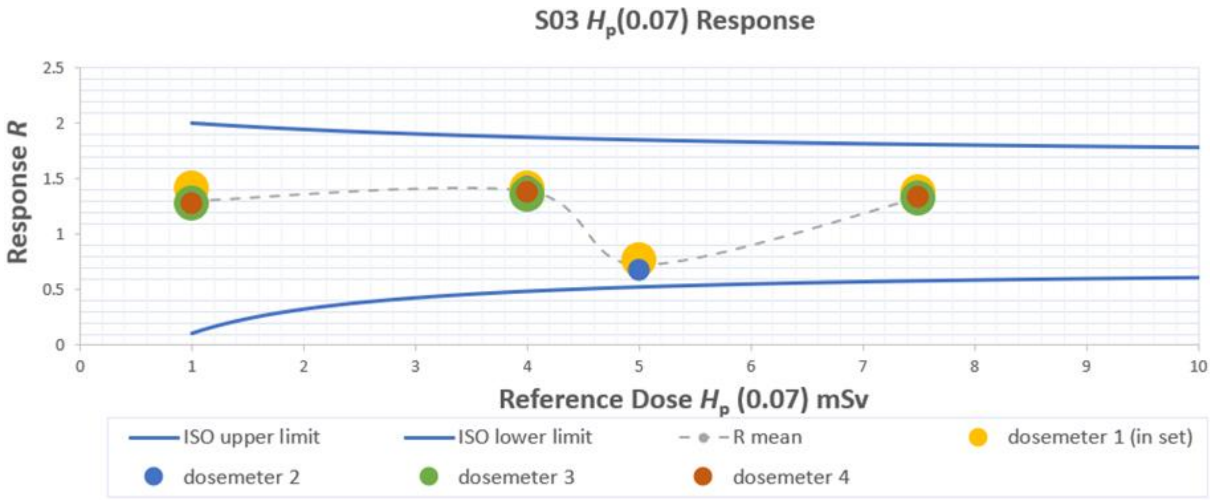


Figure 23: Dosemeter response with respect to reference dose to extremity for participant S03. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid blue lines.

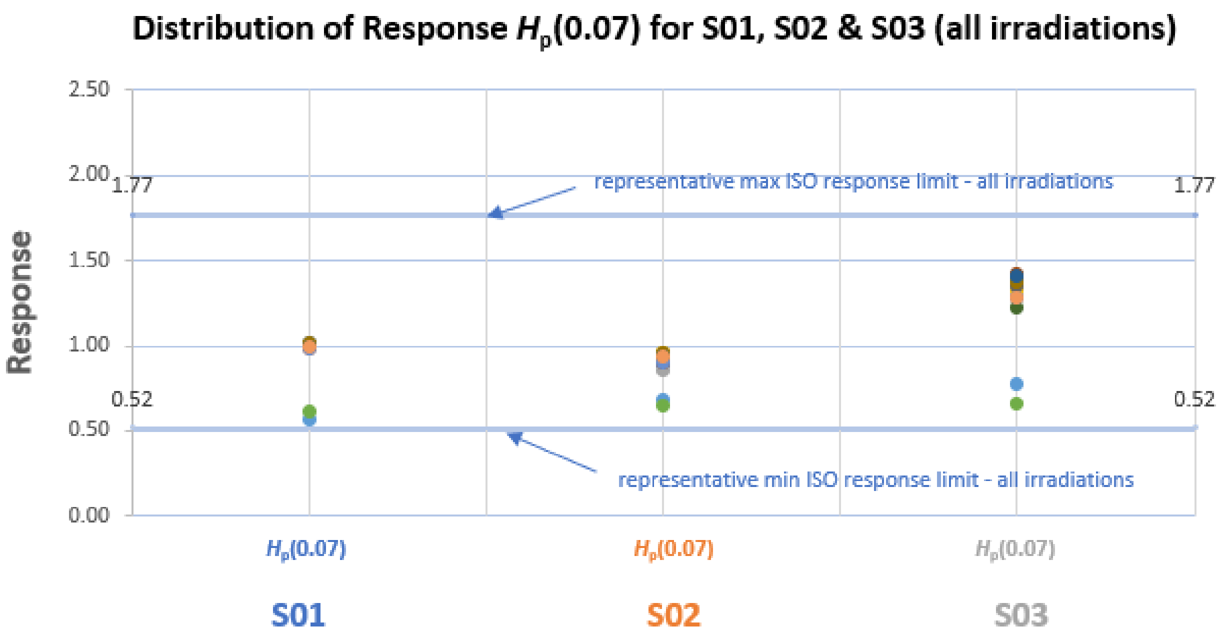


Figure 24: Distribution of response in terms of H_p(0.07) for participants S01, S02 and S03.

Table 11. Extremity dosemeter response for all irradiations.

Quality (dosem.)	Reference dose (mSv)		S01 Response *R*			S02 Response *R*			S03 Response *R*		
			Mean	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
^{90}Sr/^{90}Y (4)	$H_p(0.07)$	7.50	**1.00**	1.01	0.98	**0.91**	0.96	0.85	**1.33**	1.38	1.28
^{90}Sr/^{90}Y 45° (2)	$H_p(0.07)$	5.00	**0.60**	0.62	0.57	**0.67**	0.68	0.65	**0.72**	0.77	0.67
^{90}Sr/^{90}Y (4)	$H_p(0.07)$	4.00	**1.00**	1.01	1.00	**0.93**	0.97	0.90	**1.39**	1.42	1.36
^{90}Sr/^{90}Y (4)	$H_p(0.07)$	1.00	**1.00**	1.02	0.98	**0.93**	0.94	0.90	**1.30**	1.41	1.23

5.2. LINEARITY

Figures 23 to 25 and Table 13 show linearity of extremity dosemeter responses in terms of gradient and R^2. ***The results for the 0° irradiations are all satisfactory with all values for gradient and R^2 close to 1.***

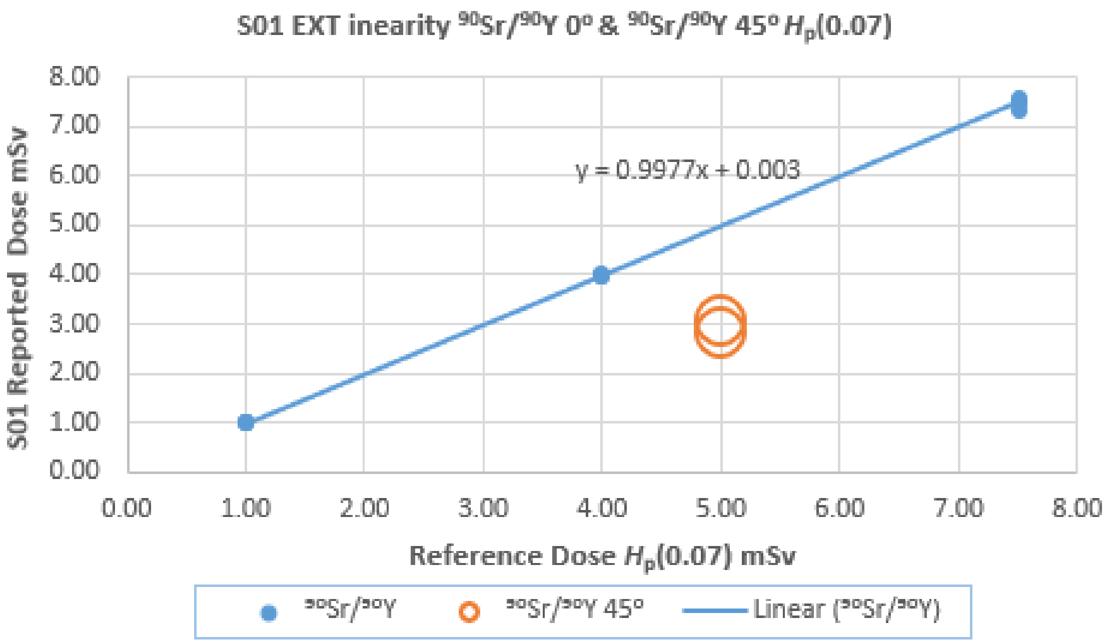


Figure 23: $H_p(0.07)$ linearity and angular response to ^{90}Sr/^{90}Y for participant S01.

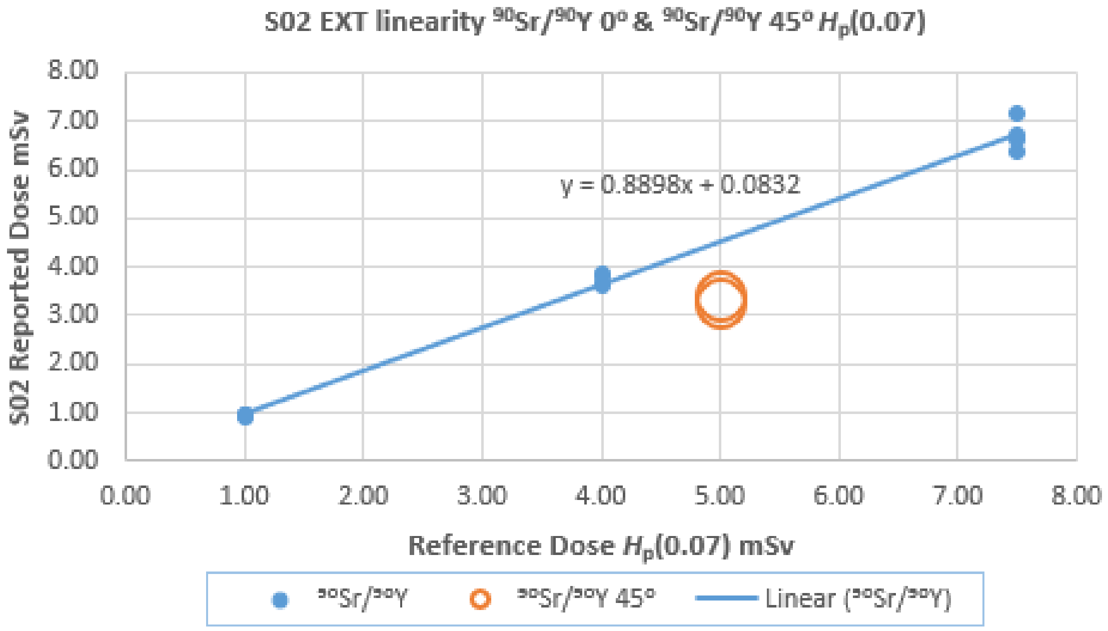


Figure 24: $H_p(0.07)$ linearity and angular response to $^{90}Sr/^{90}Y$ for participant S02.

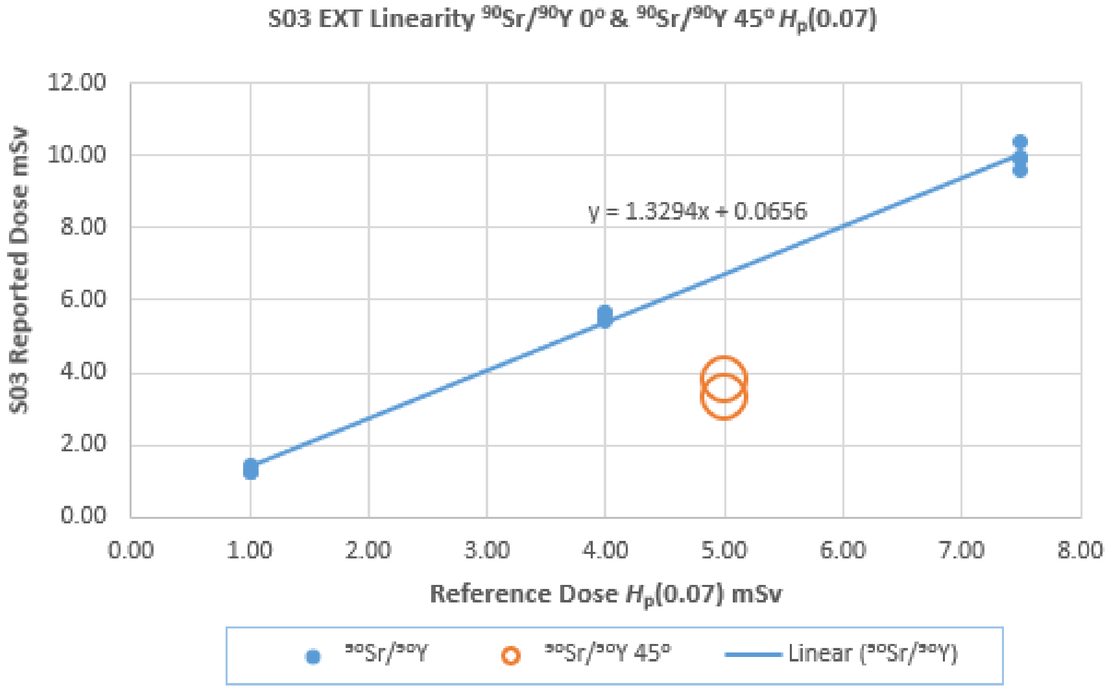


Figure 25: $H_p(0.07)$ linearity and angular response to $^{90}Sr/^{90}Y$ for participant S03.

Table 12. Linearity of extremity dosemeter response to $^{90}Sr/^{90}Y$.

Quality	Reference dose range (mSv)		S01 Response: Gradient and R^2	S02 Response: Gradient and R^2	S03 Response: Gradient and R^2
$^{90}Sr/^{90}Y$	1.0~7.5	$H_p(0.07)$	$y = 0.9977x + 0.0003$ $R^2 = 0.999$	$y = 0.8898x + 0.0832$ $R^2 = 0.999$	$y = 1.3294x + 0.0656$ $R^2 = 0.996$

5.3. ANGULAR RESPONSE

It can be seen in Figures 23 to 25 and Table 13 that extremity dosemeters from all three IMSs under-respond at 45° with ratios of 0.60, 0.67 and 0.72.

Table 13. Extremity dosemeter angular response to $^{90}Sr/^{90}Y$ (45°).

Quality (dosem.)	Reference dose (mSv)		S01 Mean response *R*	S02 Mean response *R*	S03 Mean response *R*
$^{90}Sr/^{90}Y$ (2)	$H_p(0.07)$	5.00	0.60	0.67	0.72

5.4. REPRODUCIBILITY

Table 14 shows reproducibility based on $^{90}Sr/^{90}Y$ 0° irradiations. ***Reproducibility is satisfactory, with extremity dosemeter response from participant S01 having a mean R of 1.00, from S02 0.93 and from S03 1.35.***

Table 14: Reproducibility of extremity dosemeter response.

Quality (dosem.)	Reference dose[1] (mSv)		S01 Response *R*			S02 Response *R*			S03 Response *R*		
			Mean	Max	Min	**Mean**	Max	Min	**Mean**	Max	Min
$^{90}Sr/^{90}Y$ 0° (4)	$H_p(0.07)$	7.5	**1.00**	1.01	0.98	**0.91**	0.96	0.90	**1.33**	1.38	1.28
		4.0	**1.00**	1.01	1.00	**0.93**	0.97	0.90	**1.39**	1.41	1.36
		1.0	**1.00**	1.02	0.98	**0.93**	0.94	0.90	**1.30**	1.41	1.23
CoV	$H_p(0.07)$	7.5	1.1%			4.3%			2.7%		
		4.0	0.4%			3.1%			1.7%		
		1.0	1.4%			1.9%			5.1%		

5.5. OUTLIERS

There were no outliers.

6. RESULTS AND DISCUSSION: EYE-LENS DOSIMETRY

6.1. RELATIVE RESPONSE: TRUMPET CURVES

Response, R, for each dosemeter irradiation is plotted against reference dose, $H_p(3)$, and the ISO trumpet curves for each IMS in Figures 26 and 27. Where R values for a given reference dose are very close, they may not be visible separately on the graph. ***Apart from one outlier, all the results for eye-lens dosimetry are well within the performance limits for all irradiations, thus meeting the approval criterion of ISO 14146:2018.***

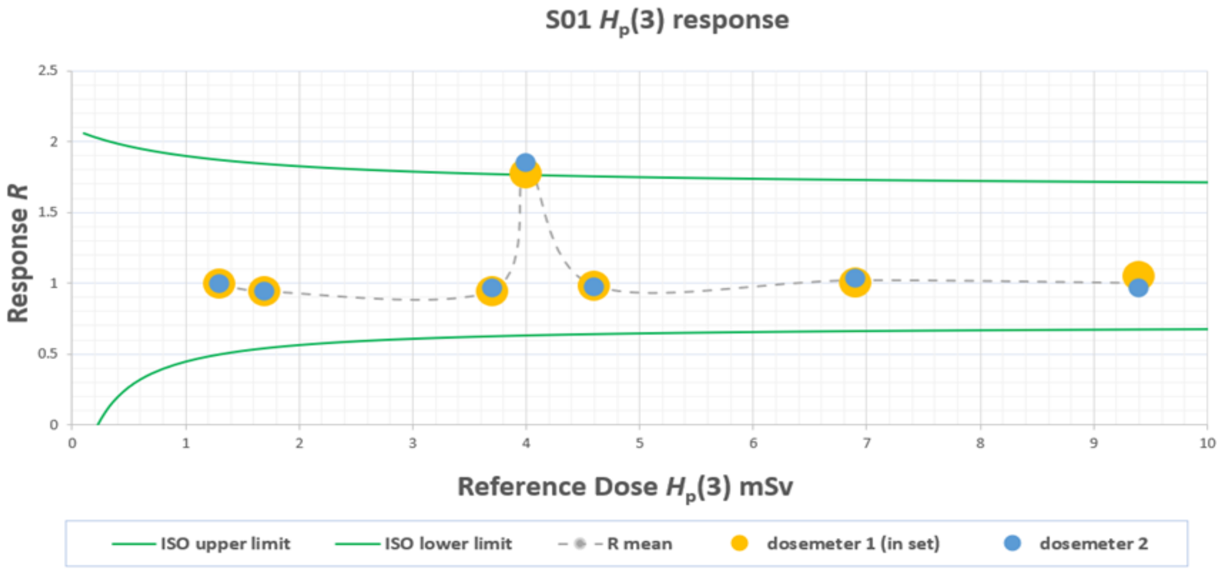


Figure 26: Dosemeter response with respect to reference dose to the eye lens for participant S01. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid green lines.

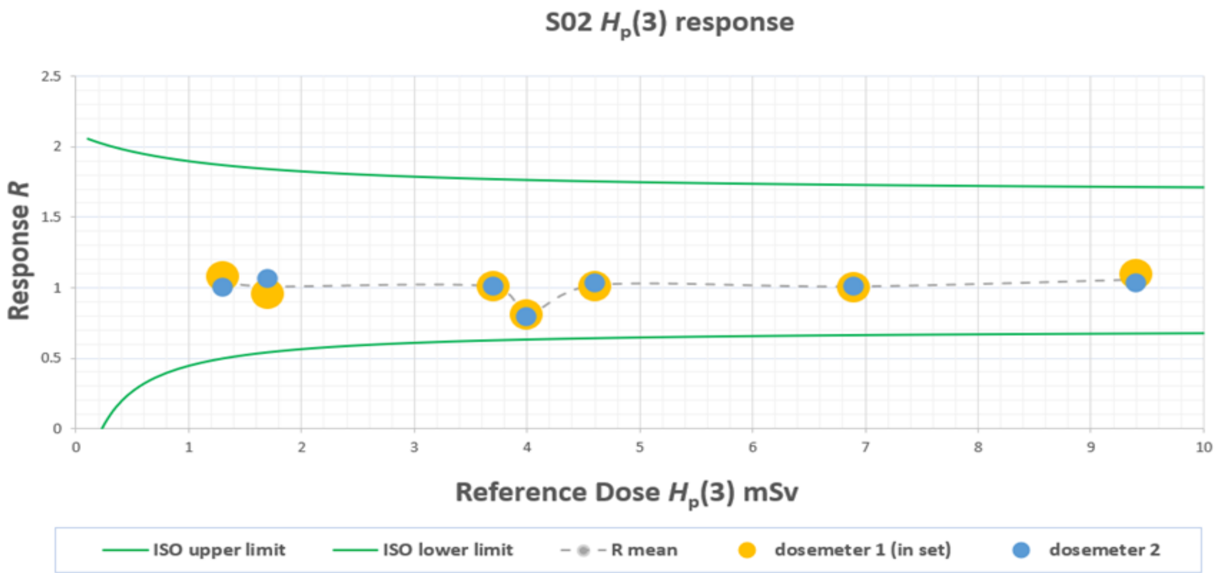


Figure 27: Dosemeter response with respect to reference dose to the eye lens for participant S02. ISO 14146:2018 performance limits (trumpet curve) are indicated by solid green lines.

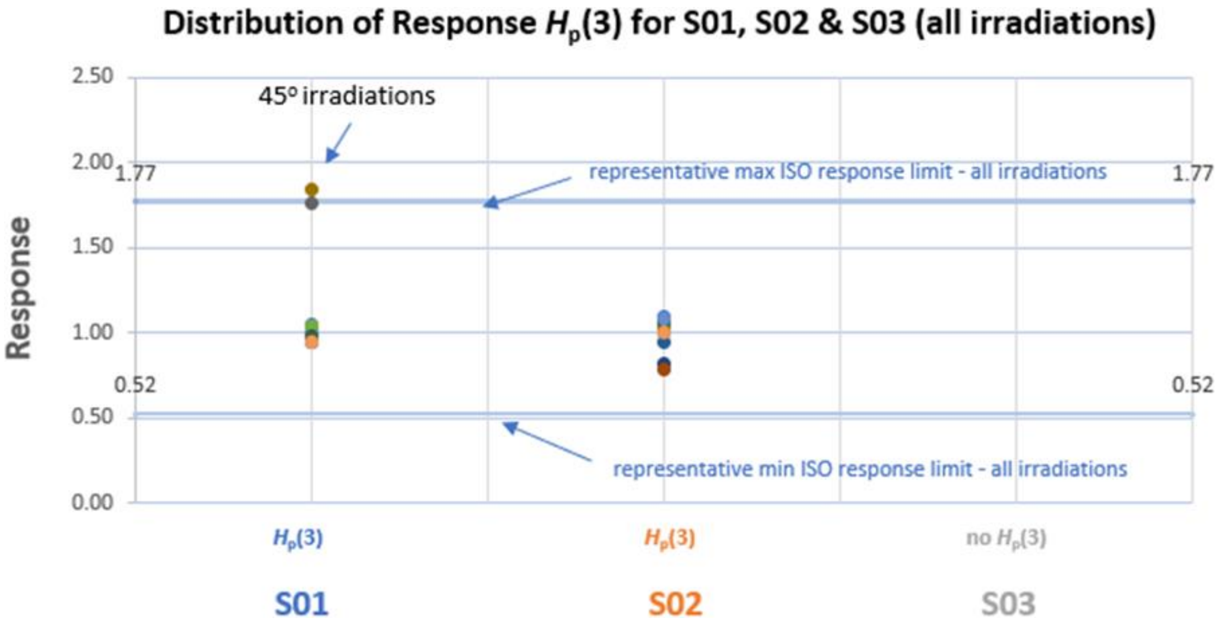


Figure 28 Distribution of response in terms of $H_p(3)$ for participants S01, S02 and S03.

Table 15. Eye-lens dosemeter response for all irradiations.

Quality (dosem.)	Reference dose (mSv)		S01			S02		
			Response *R*			Response *R*		
			Mean	Max	Min	**Mean**	Max	Min
$^{90}Sr/^{90}Y$ (2)	$H_p(3)$	9.40	**1.01**	1.05	0.96	**1.06**	1.09	1.03
$^{90}Sr/^{90}Y$ (2)	$H_p(3)$	6.90	**1.02**	1.03	1.00	**1.01**	1.01	1.00
$^{90}Sr/^{90}Y$ (2)	$H_p(3)$	4.60	**0.98**	0.98	0.97	**1.02**	1.03	1.01
$^{90}Sr/^{90}Y$ 45° (2)	$H_p(3)$	4.00	**1.81**	1.85	1.77	**0.80**	0.81	0.79
$^{90}Sr/^{90}Y$ (2)	$H_p(3)$	3.70	**0.95**	0.96	0.94	**1.01**	1.01	1.01
$^{90}Sr/^{90}Y$ (2)	$H_p(3)$	1.70	**0.94**	0.94	0.94	**1.01**	1.06	0.95
$^{90}Sr/^{90}Y$ (2)	$H_p(3)$	1.30	**0.99**	0.99	0.99	**1.04**	1.00	1.08

6.2. LINEARITY

Figures 29 and 30 as well as Table 16 show linearity of eye-lens dosemeter responses in terms of gradient and R^2. ***The results for the 0° irradiations are all satisfactory with all values for gradient and R^2 close to 1.***

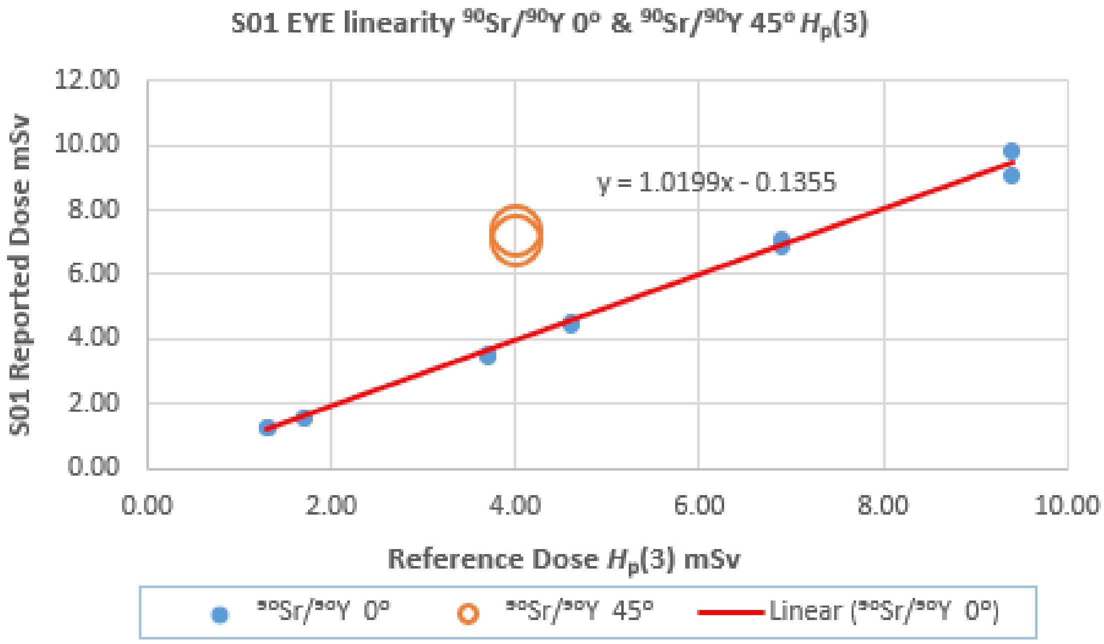


Figure 29: $H_p(3)$ linearity and angular response to $^{90}Sr/^{90}Y$ for participant S01.

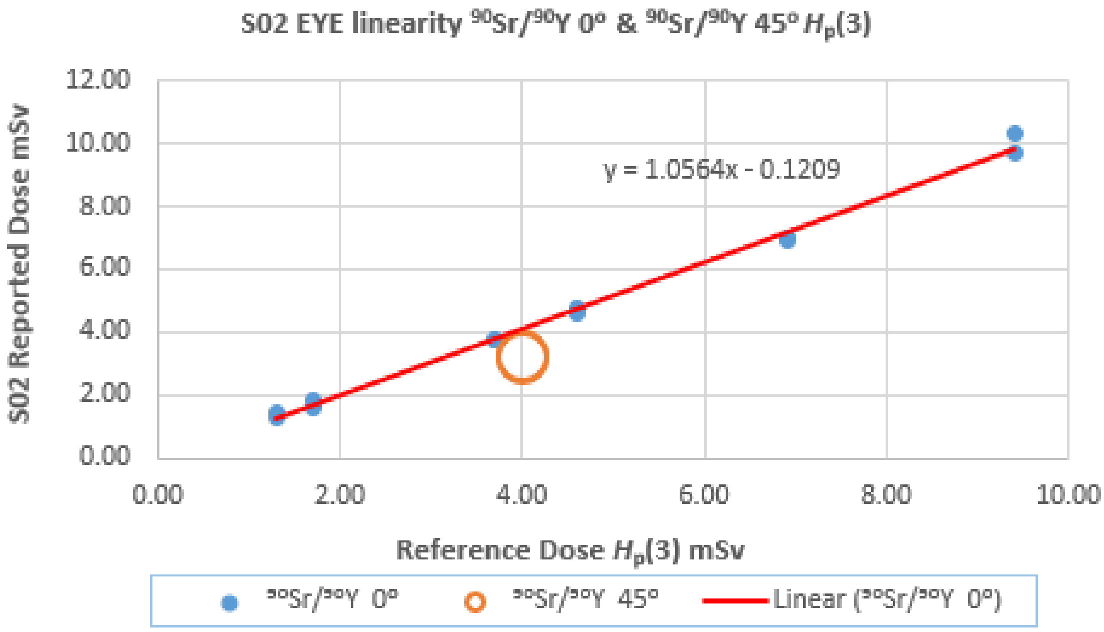


Figure 30: $H_p(3)$ linearity and angular response to $^{90}Sr/^{90}Y$ for participant S02.

Table 16. Linearity of eye-lens dosemeter response to $^{90}Sr/^{90}Y$.

Quality	Reference dose range (mSv)		S01	S02
			Response: Gradient and R^2	Response: Gradient and R^2
$^{90}Sr/^{90}Y$	1.0~10	$H_p(3)$	$y = 1.0199\,x - 0.1355$ $R^2 = 0.999$	$y = 1.0564\,x - 0.1209$ $R^2 = 0.996$

6.3. ANGULAR RESPONSE

It can be seen in Table 17 that one outlier was observed for angular response, while the response of the other dosemeter system at 45° incidence was satisfactory.

Table 17: Angular Response at 45° for $H_p(3)$ irradiations.

Quality (dosem.)	Reference dose (mSv)		S01	S02
			Mean response R	Mean response R
$^{90}Sr/^{90}Y$ 45° (2)	$H_p(3)$	4.00	1.81	0.80

6.4. OUTLIERS

Although one outlier was observed for eye-lens dosemeter response from participant S01, the approval criterion of ISO 14146:2018 was clearly met.

7. CONCLUSIONS

Dosemeter response to all radiation qualities, linearity and reproducibility were confirmed to be satisfactory. Out of 136 dosemeters irradiated there was only one outlier, but this was an over-response which was very close to the edge of the ISO 14146:2018 limit. As the ISO approval criterion allows for one-tenth of the dosemeters to exceed the performance limits, all individual monitoring services met the approval criteria for whole-body, extremity and eye-lens dosemeters.

All transit doses were low and had no impact on the results even for the lower range of the irradiations. From an overview of the results presented in the tables and figures showing linearity and angular response, it can be concluded that the interlaboratory comparisons had been successfully carried out without significant problems. This reflects very positively on the work of the organizer, the irradiation laboratories, and the participating individual monitoring services.

The proficiency testing scheme provided for an independent demonstration of the reliability and robustness of the dosimetry services involved.

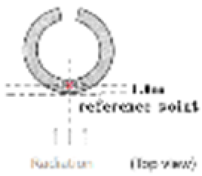
The individual monitoring services contracted by TEPCO for the assessment of external radiation exposure of workers involved in handling ALPS-treated water meet the performance limits and approval criterion specified in the international standard ISO 14146:2018.

APPENDIX I.

PROVISIONAL RESULTS AND ANALYSIS – EXAMPLE

Individual Monitoring Service S03 **ALPS-ILC-EXT**

H_p(0.07) provisional results and analysis issued: 04032024



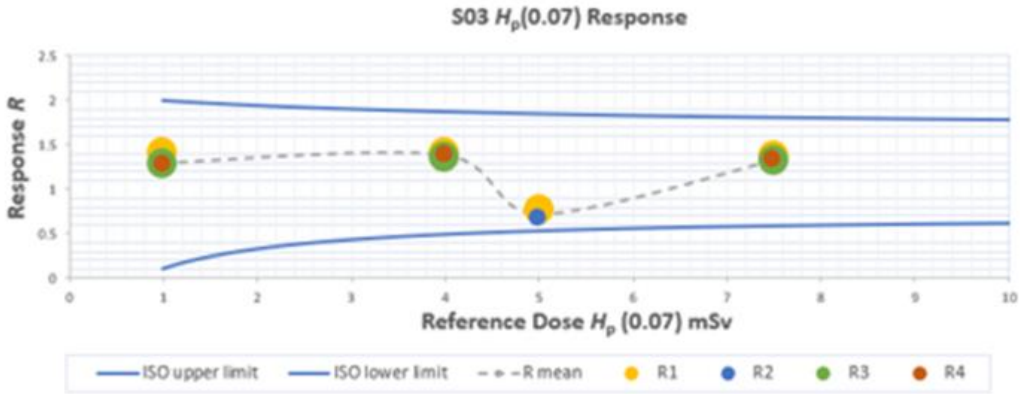
All irradiations $^{90}Sr/^{90}Y$ with reference point 2.0mm from the surface of the phantom

IMS H_p(0.07) = value (mSv) reported by IMS			Ref H_p(0.07) = value (mSv) reported by irradiating lab				
Dosemeter ID	**Angle**	**IMS H_p(0.07) mSv**	**Ref H_p(0.07) mSv**	**R IMS/Ref**	**ISO upper limit**	**ISO lower limit**	**Outlier**
S03-ILC-EXT-01	0°	10.35	7.5	1.38 *R1*	1.82	0.58	no
S03-ILC-EXT-11	0°	9.58	7.5	1.28 *R2*	1.82	0.58	no
S03-ILC-EXT-14	0°	9.91	7.5	1.32 *R3*	1.82	0.58	no
S03-ILC-EXT-18	0°	9.98	7.5	1.33 *R4*	1.82	0.58	no
S03-ILC-EXT-12	45°	3.85	5.0	0.77 *R1*	1.86	0.52	no
S03-ILC-EXT-13	45°	3.33	5.0	0.67 *R2*	1.86	0.52	no
S03-ILC-EXT-04	0°	5.65	4.0	1.41 *R1*	1.88	0.49	no
S03-ILC-EXT-06	0°	5.67	4.0	1.42 *R2*	1.88	0.49	no
S03-ILC-EXT-07	0°	5.42	4.0	1.36 *R3*	1.88	0.49	no
S03-ILC-EXT-09	0°	5.5	4.0	1.38 *R4*	1.88	0.49	no
S03-ILC-EXT-03	0°	1.41	1.0	1.41 *R1*	2.00	0.10	no
S03-ILC-EXT-05	0°	1.23	1.0	1.23 *R2*	2.00	0.10	no
S03-ILC-EXT-15	0°	1.28	1.0	1.28 *R3*	2.00	0.10	no
S03-ILC-EXT-19	0°	1.28	1.0	1.28 *R4*	2.00	0.10	no
S03-ILC-EXT-02	Wrong irradiation	1.23	Note1: *R* IMS/Ref *R* (either *R1*, *R2*, *R3* or *R4*) for each dosemeter irradiation is plotted against Dose H_p(0.07) mSv in the graph below. Where *R* values for a given dose are very close they may not be visible separately on the graph. ISO lower limit for H_p(0.07) is 1.0mSv.				
S03-ILC-EXT-20	Wrong irradiation	1.37					
S03-ILC-EXT-21	Wrong irradiation	1.40					
S03-ILC-EXT-22	Wrong irradiation	1.47	Note 2: uncertainties The reported expanded uncertainties (k=2) for reference irradiations were 4.5% for 0° and 5.1% for +45° as determined in accordance with JCGM 100:2008.				
S03-ILC-EXT-08	Not irradiated	0.15					

S03 H_p (0.07) results and analysis issued 04032024

IAEA

IMS $H_p(0.07)$ = value (mSv) reported by IMS			Ref $H_p(0.07)$ = value (mSv) reported by irradiating lab				
Dosemeter ID	**Angle**	**IMS $H_p(0.07)$ mSv**	**Ref $H_p(0.07)$ mSv**	***R* IMS/Ref**	**ISO upper limit**	**ISO lower limit**	**Outlier**
S03-ILC-EXT-10	Not irradiated	0.14	Note 3: ISO 14146:2018 approval criterion: *A maximum of 1/10 (ie 2 in this sample) of the irradiated dosemeters may exceed the performance limits.* **It can be seen from the reported *R* values and the graph that all dosemeters have met the ISO approval criteria for all test radiation qualities and angles.**				
S03-ILC-EXT-16	Not irradiated	0.15					
S03-ILC-EXT-17	Not irradiated	0.15					



Response *R* as a function of reference dose with ISO 14146:2018 performance limits

APPENDIX II.

CERTIFICATE OF PARTICIPATION – EXAMPLE

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

IAEA Review of Safety Related Aspects of Handling ALPS Treated Water at TEPCO's Fukushima Daiichi Nuclear Power Station

Extremity Dosemeter Intercomparison – ALPS-ILC-EXT-2023

Certificate of Participation – $H_p(0.07)$

Certificate Number:	ALPS-ILC-EXT-2023 certificate: 003
Number of Pages:	4
Date of Issue:	31 March 2024
Participating IMS:	S03
Dosimetry System Details:	
Reporting Number:	S03
Results:	See pages 2 & 3
Procedure :	See page 4 for details of Performance Criteria ISO 14146: 2018

Timetable:	
Irradiations	18 January 2024
Dosemeters returned to IMS	18 January 2024
IMS sent results to Co-ordinator	30 Jan 2024
Co-ordinator issued provisional results *R* (reported/reference)	05 March 2024
IMS send any comments to Co-ordinator	05 March 2024
Co-ordinator issues final "Certificates of Participation"	31 March 2024

Number of Participants:	3
Co-ordinator	Andrew McWhan
Organising Authority	IAEA Radiation Safety Technical Services Laboratory
Irradiations – $H_p(0.07)$	CIEMAT Ionizing Radiations Metrology Laboratory - Spain See Report P7658/LMRI/BP/5610

Signed on behalf of the Organising Authority:

Co-ordinator — Andrew McWhan

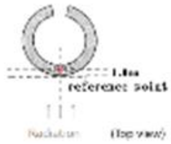
Organising Authority — Rodolfo Cruz-Suarez

S03 $H_p(0.07)$ EXT Certificate of Participation issued 31 March 2024

Page 1 of 4

Individual Monitoring Service S03 ALPS-ILC-EXT

$H_p(0.07)$ results and analysis



All irradiations $^{90}Sr/^{90}Y$ with reference point 2.0mm from the surface of the phantom

IMS $H_p(0.07)$ = value (mSv) reported by IMS			Ref $H_p(0.07)$ = value (mSv) reported by irradiating lab				
Dosemeter ID	**Angle**	**IMS $H_p(0.07)$ mSv**	**Ref $H_p(0.07)$ mSv**	***R* IMS/Ref**	**ISO upper limit**	**ISO lower limit**	**Outlier**
S03-ILC-EXT-01	0°	10.35	7.5	**1.38** *R1*	1.82	0.58	no
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S03-ILC-EXT-13	45°	3.33	5.0	**0.67** *R2*	1.86	0.52	no
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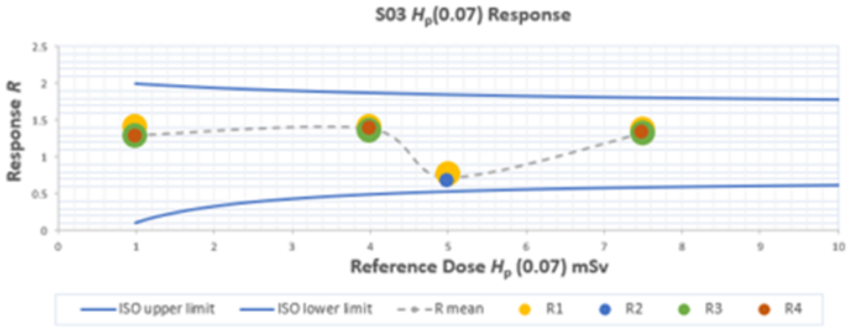
S03-ILC-EXT-03	0°	1.41	1.0	**1.41** *R1*	2.00	0.10	no
S03-ILC-EXT-05	0°	1.23	1.0	**1.23** *R2*	2.00	0.10	no
S03-ILC-EXT-15	0°	1.28	1.0	**1.28** *R3*	2.00	0.10	no
S03-ILC-EXT-19	0°	1.28	1.0	**1.28** *R4*	2.00	0.10	no
S03-ILC-EXT-02	Wrong irradiation	1.23	Note1: *R* IMS/Ref *R* (either *R1*,*R2*,*R3* or *R4*) for each dosemeter irradiation is plotted against Dose $H_p(0.07)$ mSv in the graph below. Where *R* values for a given dose are very close they may not be visible separately on the graph. ISO lower limit for $H_p(0.07)$ is 1.0mSv.				
S03-ILC-EXT-20	Wrong irradiation	1.37					
S03-ILC-EXT-21	Wrong irradiation	1.40					
S03-ILC-EXT-22	Wrong irradiation	1.47	Note 2: uncertainties The reported expanded uncertainties (k=2) for reference irradiations were 4.5% for 0° and 5.1% for +45° as determined in accordance with JCGM 100:2008.				
S03-ILC-EXT-08	Not irradiated	0.15					

S03 $H_p(0.07)$ EXT Certificate of Participation issued 31 March 2024

IAEA

Page 2 of 4

IMS $H_p(0.07)$ = value (mSv) reported by IMS			Ref $H_p(0.07)$ = value (mSv) reported by irradiating lab				
Dosemeter ID	Angle	IMS $H_p(0.07)$ mSv	Ref $H_p(0.07)$ mSv	*R* IMS/Ref	ISO upper limit	ISO lower limit	Outlier
S03-ILC-EXT-10	Not irradiated	0.14	Note 3: ISO 14146:2018 approval criterion: *A maximum of 1/10 (ie 1 in this sample) of the irradiated dosemeters may exceed the performance limits.* **It can be seen from the reported *R* values and the graph that all dosemeters have met the ISO approval criteria for all test radiation qualities and angles.**				
S03-ILC-EXT-16	Not irradiated	0.15					
S03-ILC-EXT-17	Not irradiated	0.15					



Response *R* as a function of reference dose with ISO 14146:2018 performance limits

Procedure and Performance Criteria – ISO 14146: 2018

ALPS IC2023 has been set up to demonstrate IMS compliance with the ISO standard (ISO 14146, 2018) "Criteria and performance limits for the periodic evaluation of dosimetry services". The performance limits set by ISO 14146 are adopted and used to generate the "trumpet curves" :

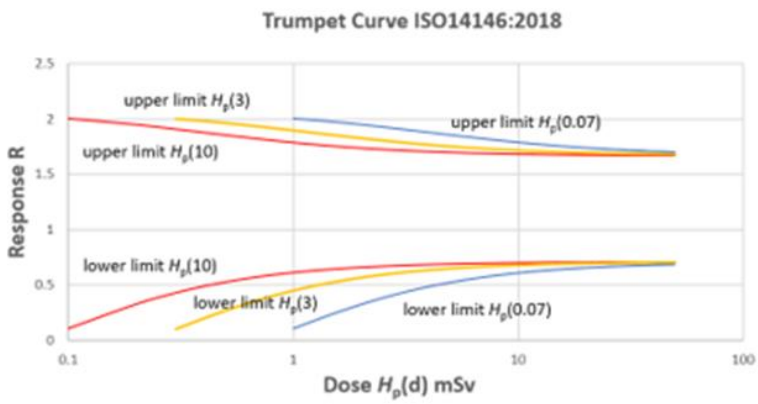
$$0.71 \cdot \left(1 - \frac{2 \cdot \frac{H_0}{1.33}}{\frac{H_0}{1.33} + H_c}\right) \leq R \leq 1.67 \cdot \left(1 + \frac{H_0}{4 \cdot H_0 + H_c}\right)$$

R is the IMS response, H_c is the conventional true value (reference dose as reported by the irradiating laboratory) and H_0 is the "lower dose limit below which irradiations should not be performed":

- H_0 = 0.1 mSv for whole body dosemeters measuring $H_p(10)$
- H_0 = 0.3 mSv for eye lens dosemeters measuring $H_p(3)$
- H_0 = 1 mSv for extremity dosemeters measuring $H_p(0.07)$

The Organising Authority, ie IAEA Radiation Safety Technical Services Laboratory, arranged the basic schedule and irradiation plan but the actual doses were set by the Irradiation Laboratories with details sent in-confidence to the Co-ordinator. After dosemeter evaluation the IMS sent the results to the Co-ordinator who issued draft reports to each IMS showing R (reported value/reference dose). There is no direct contact between the IMS and the Irradiation Laboratories. The Co-ordinator ensures confidentiality of the reference dose information until after all the participating IMS have evaluated the dosemeters and issued the results.

For the analysis of the results in this report, any result exceeding the above performance limits would be considered as an outlier. The standard ISO 14146:2018 allows a maximum of one-tenth of the dosemeters irradiated to exceed these limits.



Explanation

The accuracy of dosemeters is significantly reduced at low doses because of the technical limits of all the various dosimetry systems. The ISO standards recognise these technical limitations. To meet the ISO standards dosemeters must be able to measure doses to an accuracy within the limits set by the "trumpet curves". It can be seen from the graph above that the standards are more lenient at the lower dose range as the "trumpet" width increases. The x axis shows the reference dose, ie the dose given to the dosemeters by the Irradiating Laboratory and the y axis shows the response ratio of the reported dose / reference dose.

REFERENCES

[1] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Review of Safety Related Aspects of Handling ALPS Treated Water at TEPCO's Fukushima Daiichi Nuclear Power Station – Report 3: Status of IAEA's Independent Sampling, Data Corroboration, and Analysis Activities, IAEA, Vienna (2022).

[3] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Conformity Assessment – General Requirements for Proficiency Testing, ISO 17043:2010, ISO, Geneva (2010).

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[12] JOINT COMMITTEE FOR GUIDES IN METROLOGY, International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM), JCGM 200:2012, JCGM (2012).

[13] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, INTERNATIONAL ELECTROTECHNICAL COMMISSION, General Requirements for the Competence of Testing and Calibration Laboratories, ISO/IEC 17025:2017, ISO, Geneva (2017).

DEFINITIONS

The following definitions reproduced from [3], [4], [11] and [12] apply for the purposes of this report.

The symbol '🛈' *denotes an information note.*
The symbol '!' *denotes a cautionary note.*
Notes do not constitute part of the definition.

absorbed dose

The fundamental dosimetric quantity *D*, defined as:

$$D = \frac{d\bar{\varepsilon}}{dm}$$

where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter in a volume element and d*m* is the mass of matter in the volume element.

🛈 The energy can be averaged over any defined volume, the average *dose* being equal to the total energy imparted in the volume divided by the mass in the volume.

🛈 Absorbed dose is defined at a point.

🛈 The SI unit for absorbed dose is joule per kilogram (J/kg), termed the gray (Gy) (formerly, the rad was used).

assigned value

value attributed to a particular property of a proficiency test item.

coordinator

one or more individuals with responsibility for organizing and managing all of the activities involved in the operation of a proficiency testing scheme.

control (background) dosemeter

Personal or area *dosemeter* that provides an estimate of any radiation dose received by the evaluation sample apart form that given by the irradiating laboratory.

🛈 The control dosemeter provides a means of estimating and eliminating the contribution to the dose from background radiation and that received during the time between zeroing and read out, i.e., the dose during handling and transportation.

conventional quantity value

Quantity value attributed by agreement to a *quantity* for a given purpose.

dose

A measure of the energy deposited by radiation in a target.

dose equivalent

The product of the *absorbed dose* at a point in the tissue or organ and the appropriate *quality factor* for the type of *radiation* giving rise to the *dose*.

ⓘ A measure of the dose to a tissue or organ designed to reflect the amount of harm caused.

ⓘ For radiation protection purposes, the quantity *dose equivalent* has been superseded by equivalent dose.

ⓘ *Dose equivalent* is also a term used by the International Commission on Radiation Units and Measurements in defining the following operational quantities: ambient dose equivalent, directional dose equivalent and *personal dose equivalent*.

dosemeter

Radiation meter designed to measure quantities such as an absorbed dose or dose equivalent.

ⓘ In a wider sense, this term is used for meters designed to measure other quantities related to radiation such as exposure, fluence, etc. Such use is deprecated.

ⓘ This apparatus may require a separate reader to read out the *absorbed dose* or *dose equivalent*.

dosimetry service

Organization that operates a personal and/or area dosimetry system which includes the evaluation of the reading of *dosemeters* after their use and includes:

- providing the user with *dosemeters*;
- recording the results;
- reporting the results to the user.

ⓘ The *dosimetry service* fulfils basic quality management and independency requirements if it fulfils the requirements stated in ISO/IEC 17025 [13].

ⓘ The user includes not only external clients but also internal personnel who wear *dosemeters* provided by their organization and are engaged in radiation protection activities inside or outside the organization. The same quality of *dosimetry service* which is provided to external users is also provided to organizations' employees (internal users), in accordance with their own quality management system.

exposure

The state or condition of being subject to irradiation.

! *Exposure* should not be used as a synonym for *dose*. *Dose* is a measure of the effects of *exposure*.

ⓘ *Exposure* to ionizing radiation can be broadly divided into exposure categories according to the status of the individual(s) exposed; into exposure situations according to the circumstances of the *exposure*; and according to the source of the *exposure*.

external exposure

Exposure to radiation from a source outside the body.

ⓘ Contrasted with *internal exposure*.

indicated value

Value of the measurand given directly by a measuring instrument on the basis of its calibration curve.

- ⓘ In this document, the indicated value is the one given by the dosimetry system as the final result of the evaluation algorithm (for example, display of the software, print out) in units of *dose equivalent* (Sv).

- ⓘ It may be necessary that a measured *dose* (e.g., by *control dosemeters*) or a calculated transport and/or background dose be subtracted by the *dosimetry service* or by the evaluating organization.

indication

Quantity value provided by a measuring instrument or a measuring system.

individual monitoring

Monitoring using measurements by equipment worn by individuals, or measurements of quantities of radioactive substances in or on, or taken into, the bodies of individuals, or measurements of quantities of radioactive substances excreted from the body by individuals.

- ⓘ Also called personal monitoring.

- ⓘ For workers, usually contrasted with workplace monitoring.

individual monitoring service

Synonymous with *dosimetry service*.

interlaboratory comparison

Organization, performance and evaluation of measurements or tests on the same or similar items by two or more laboratories in accordance with predetermined conditions.

internal exposure

Exposure to radiation from a source within the body.

- ⓘ Contrasted with *external exposure*.

irradiated dose

Conventional quantity value of the dose to which the dosemeter is irradiated.

measurand

Quantity intended to be measured.

monitoring

The measurement of *dose*, dose rate or activity for reasons relating to the assessment or control of *exposure* to radiation or exposure due to radioactive substances, and the interpretation of the results.

- ⓘ ‘Measurement’ is used somewhat loosely. The ‘measurement’ of *dose* often means the measurement of a *dose equivalent* quantity as a proxy (i.e., substitute) for a *dose* quantity that cannot be measured directly. Also, sampling may be involved as a preliminary step to measurement.
- ⓘ Measurements may actually be of radiation levels, airborne activity concentrations, levels of contamination, quantities of radioactive material or individual *doses*.
- ⓘ The results of these measurements may be used to assess radiological hazards or *doses* resulting or potentially resulting from *exposure*.
- ⓘ Monitoring may be subdivided in two different ways: according to where the measurements are made, into *individual monitoring*, workplace monitoring, source monitoring and environmental monitoring; and, according to the purpose of the *monitoring*, into routine monitoring, task related monitoring and special monitoring.

outlier

Observation in a set of data that appears to be inconsistent with the remainder of that set.

- ⓘ An *outlier* can originate from a different population or be the result of an incorrect recording or other gross error.

participant

Laboratory, organization or individual that receives proficiency test items and submits results for review by the proficiency testing provider.

personal dose equivalent

The *dose equivalent* in soft tissue below a specified point on the body at an appropriate depth *d*.

- ⓘ Parameter used as a directly measurable proxy (i.e., substitute) for equivalent dose in tissues or organs or (with $d = 10$ mm) for effective dose, in *individual monitoring* of *external exposure*.
- ⓘ The recommended values of d are 10 mm for strongly penetrating radiation and 0.07 mm for weakly penetrating radiation for whole-body *monitoring*.
- ⓘ $H_p(0.07)$ is used for *monitoring* for hands and feet for all radiation types.
- ⓘ $H_p(3)$ is used for *monitoring exposure* of the lens of the eye.
- ⓘ ‘Soft tissue’ is commonly interpreted as the International Commission on Radiation Units and Measurements (ICRU) sphere.

precision

Closeness of agreement between indications or measured *quantity values* obtained by replicate measurements on the same or similar objects under specified conditions.

proficiency testing

Evaluation of participant performance against pre-established criteria by means of *interlaboratory comparisons*.

proficiency testing scheme

Proficiency testing designed and operated in one or more rounds for a specified area of testing, measurement, calibration or inspection.

quality factor

A number by which the *absorbed dose* in a tissue or organ is multiplied to reflect the relative biological effectiveness of the radiation, the result being the *dose equivalent*.

> ⓘ Superseded by radiation weighting factor in the definition of equivalent dose, but still defined, as a function of linear energy transfer, for use in calculating the *dose equivalent* quantities used in *monitoring*.

quantity

Property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference.

quantity value

Number and reference together expressing magnitude of a *quantity*.

response

Quotient of the *indicated value* of a quantity and the *conventional quantity value* of that quantity.

reproducibility

Measurement *precision* under reproducibility conditions of measurement.

reproducibility conditions

Condition of measurement, out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects.

uncertainty

Non-negative parameter characterizing the dispersion of the *quantity values* being attributed to a measurand, based on the information used.